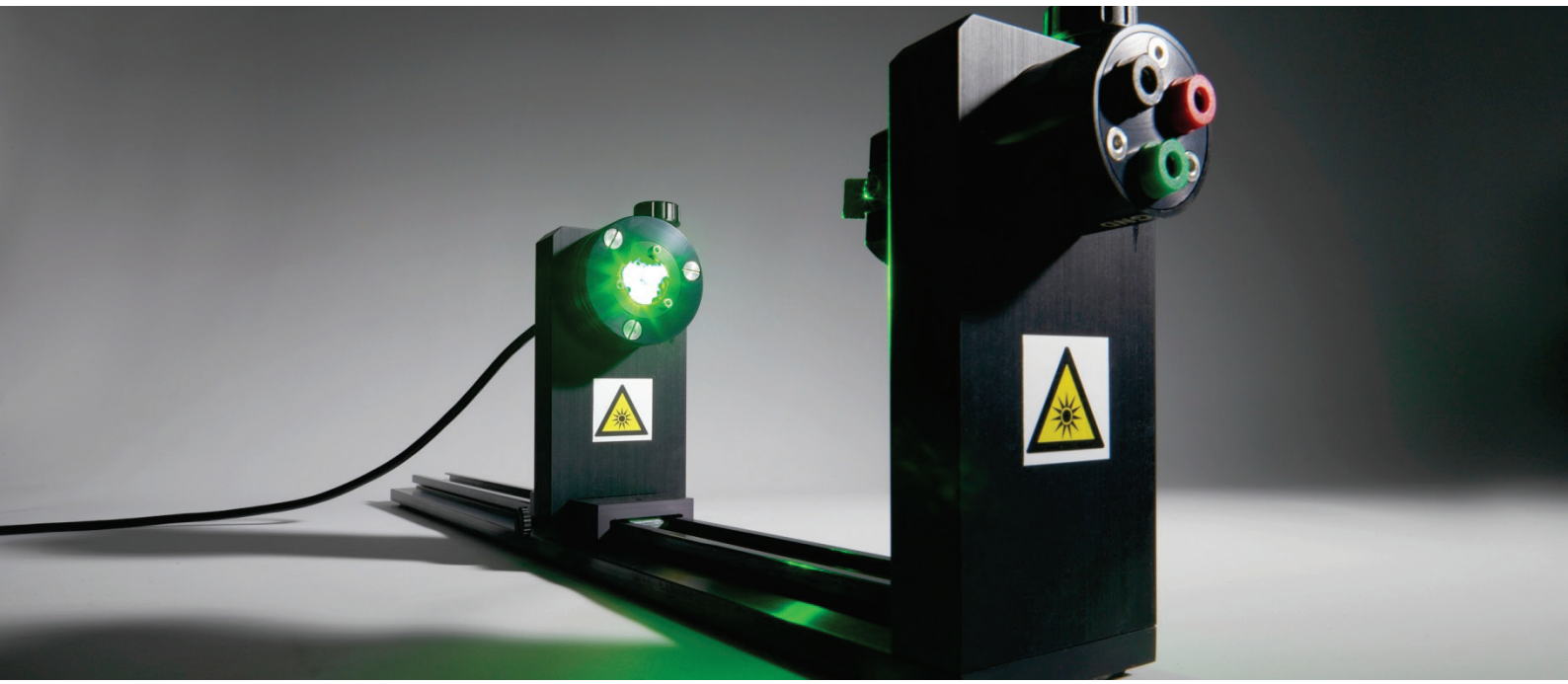
LED Driver

User manual



Metrohm
Autolab B.V.

Please read this manual carefully before starting to use the Autolab LED Driver kit

The next sections deal with appearance and use of the equipment and contain necessary information regarding operation and installation.

SAFETY PRACTICES

General

- The following safety practices are intended to ensure safe operation of the equipment and must be observed during all phases of operation, service and repair of the instrument.
- Failure to follow these instructions may cause unsafe operation.
- Metrohm Autolab is not liable for any damage caused by not complying with the safety requirements.
- Failure to follow these instructions may void any warranty provided to this product.

Electrical hazards

- To avoid electric shock hazard, always ground the equipment by using the provided power adaptor.
- There are no user-serviceable parts. Equipment installation, component replacement and internal adjustments must be done only by qualified personnel.
- Opening the equipment poses a risk of exposure to potentially dangerous voltages.
- Please also refer to the Electrical Hazards described separately for the Autolab instrument used.

General precautions

- Use only stable surfaces for setting up the system.
- Do not look directly at the light coming out of the light source.
- Allow the light source to cool down after prolonged used at high driving currents.

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Autolab PGSTAT in combination with LED Driver

The characterization of optical energy conversion devices (i.e. solar cells) requires controlled illumination from a light source. Depending on the experimental requirements, the light source can be a solar simulator, a simple LED, or a laser. This light source must be programmable in order to expose the device under test (DUT) to a user-defined light intensity. The type of light profile depends on the experimental conditions.

Information

This document provides basic information regarding the Autolab LED Driver and the associated products. This kit is controlled through the NOVA software. Additional resources are available online (www.metrohm-autolab.com/support).

This manual describes the use of the Autolab LED Driver and LED light source in combination with the Autolab PGSTAT.

Note

The LED Driver is compatible with all Autolab PGSTAT instruments **except** the Autolab PGSTAT302F. In this manual, the term Autolab is used to describe any type of compatible instrument.

The following measurement techniques are possible with the LED Driver in combination with the Autolab PGSTAT:

- Polarization curves and power density curves
- Charge extraction measurements
- Electrochemical impedance spectroscopy at constant illumination
- Intensity-modulated photovoltage spectroscopy (IMVS)
- Intensity-modulated photocurrent spectroscopy (IMPS)

It is also possible to combine all the measurement techniques in a single experiment.

Warning

This device must be used carefully to prevent personal injury. Metrohm Autolab is not responsible for physical injuries sustained while using this product. It is advised to read this documentation very carefully before operating this equipment. Please contact Metrohm Autolab (info@metrohm-autolab.com) in case of problems.

Whenever applicable, a hot surface warning label or strong optical radiation warning label are used in this manual as reminder to the hazards that can be encountered when operating this equipment.

Warning

This warning symbol is used in this document to indicate a hot surface hazard related to the heat dissipation in the light source. Allow the system to cool down after prolonged use.

Warning

This warning symbol is used in this document to indicate an optical hazard related to highly focused beam of light generated by the LED light source. Do not look directly into the light beam when the light source is on.

1 – Scope of delivery

The LED Driver kit is supplied with the following items:

- Autolab LED Driver box
- Power adaptor
- 50 Ω terminator plug
- 6 BNC to SMB adaptor plugs
- 3 SMB shielded cables (1 m)
- 1 BNC shielded cable (1 m)
- 1 BNC shielded cable (2 m)
- 2 BNC shielded cable (50 cm)
- DIO to BNC cable for Autolab N series PGSTAT instruments and µAutolab
- DIO to BNC cable for Autolab PGSTAT101 and M101 module
- Optical bench

The LED Driver kit is intended to be used with the Autolab LED light source, included with the LED Driver:

- 1 LED array cover (627 nm), 700 mA maximum current
- 1 LED cover holder
- 1 LED cover holder connection cable (2 m)
- 1 calibrated photodiode holder with calibration certificate

Additional accessories are available for the Autolab LED light source:

- Additional LED covers (see Section 4.2 for more information)
- Additional LED cover holders

Figure 1 shows a complete overview of the LED Driver kit items.

Figure 1 – The LED Driver kit, including optical bench, light source and photodiode holder

The three SMB/SMB shielded cables can be fitted with SMB to BNC adaptor plugs. Depending on the type of FRA module used in combination with the LED Driver, these cables can be modified accordingly:

- For the FRA2 module, the cables must be fitted with SMB to BNC adaptors on both ends (see Figure 2).

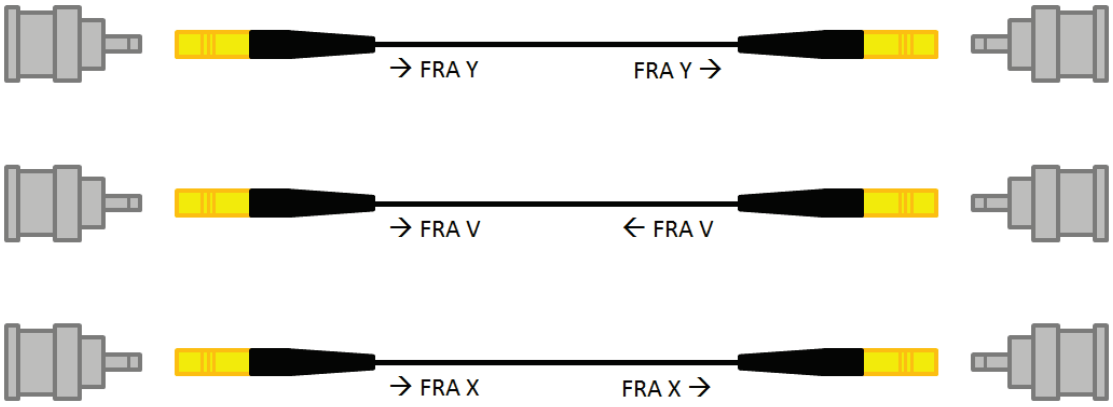


Figure 2 – Configuration of the SMB cables used in combination with the FRA2 module

- For the FRA32M module, the cables must be fitted with SMB to BNC adaptors on a single end (see Figure 3).

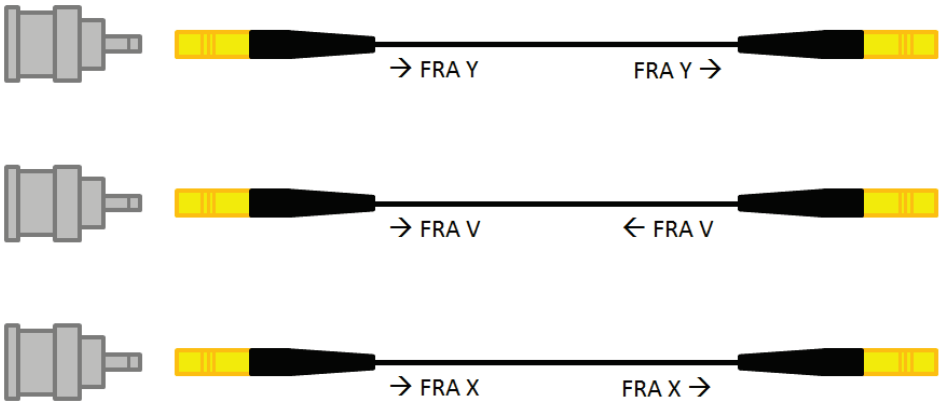


Figure 3 - Configuration of the SMB cables used in combination with the FRA32M module

2 – Hardware requirements

The experimental setups described in this manual require the following hardware:

- Autolab PGSTAT, µAutolab[1] or Multi Autolab (for DC measurements)
- FRA2 or FRA32M module (for AC measurements)
- Autolab LED Driver
- Autolab LED cover with holder

Warning

The LED Driver has a working range of 0-10 V, which means that the FRA2 modules must be modified to the 0-10 V input range. The hardware setup must be adjusted accordingly (see Appendix 1).

[1] The µAutolab can only be used for DC measurements.

3 – Software requirements

The experimental setups described in this manual require the following software:

- Latest version of NOVA

This manual assumes that the reader is familiar with the operation of the Autolab instrument in combination with the NOVA software. More information on the software tools used in this manual can be found in the following document, available from the Help – Tutorials menu in NOVA:

- Autolab control tutorial
- External devices tutorial
- Impedance spectroscopy tutorial
- NOVA Getting started
- NOVA User manual
- Command list

4 – Installation

This section describes the required connections between the Autolab PGSTAT and the Autolab LED driver.

The combination of the PGSTAT with a LED driver is a very useful hardware construction which allows measurements at controlled light intensity on solar cells. In this setup, the LED Driver is used to control the output of the light source while the Autolab PGSTAT is used to measure the potential and current on the device under test (DUT).

The LED Driver can be operated in constant output mode or in modulated output (which requires the FRA2 or FRA32M module). The Autolab PGSTAT can be operated in potentiostatic mode or in galvanostatic mode.

4.1 – Autolab LED driver

The Autolab LED driver is an analog and digitally programmable constant current source which can be used to supply a driving current to a LED or a LED array (see Figure 4). The maximum driving current which can be generated by the LED driver is 1000 mA DC.

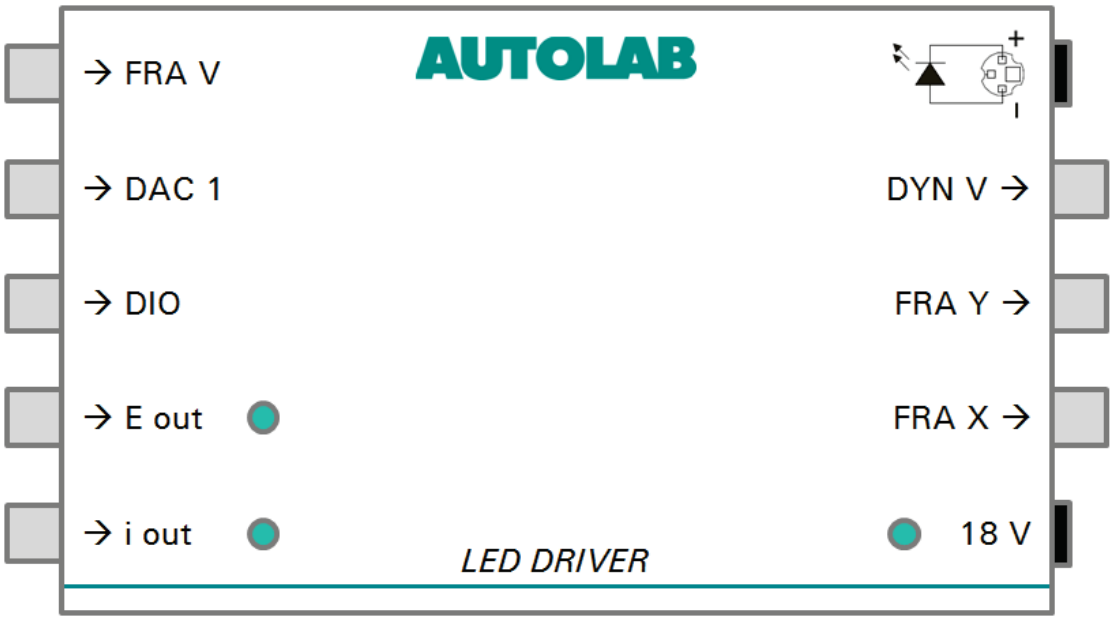


Figure 4 – Top view of the Autolab LED driver

The LED driver provides the following functionality:

1. A dual analog programmable input (→ FRA V and → DAC 1) for direct control of the LED current supplied by the driver.
2. A current to voltage converter for direct analog readout of the driving current (FRA Y →).
3. A dual input feedthrough for the Autolab E_{out} and i_{out} signals to the FRA → X output. The input is controlled by a DIO triggered switch (→ DIO input).

The LED Driver is designed to control a dedicated LED array of three, 1000 mA rated LEDs, provided by Metrohm Autolab (see Section 4.2 for more information). This light source is recommended for this application and will be assumed in the rest of the document.

Note

The light source is a critical component of this hardware setup and it should be chosen carefully. Light sources like LEDs are economical and offer a narrow spectral distribution. Laser diodes can also be used. Both light sources have a low power output. Alternative light sources can be used however their use fall outside of the scope of this manual.

When working in combination with the FRA2 or FRA32M module, the maximum frequency that can be used in combination with the LED driver is 20 kHz. The maximum frequency is limited by the voltage-to-current converter in the LED driver.

4.1.1 – Basic connections

Figure 5 shows an overview of the basic connections to and from the LED driver. All the connectors located on the left-hand side of the driver are input connections from the Autolab PGSTAT to the LED driver. The BNC connectors located on the right-hand side of the driver are the output connections to the Autolab PGSTAT.

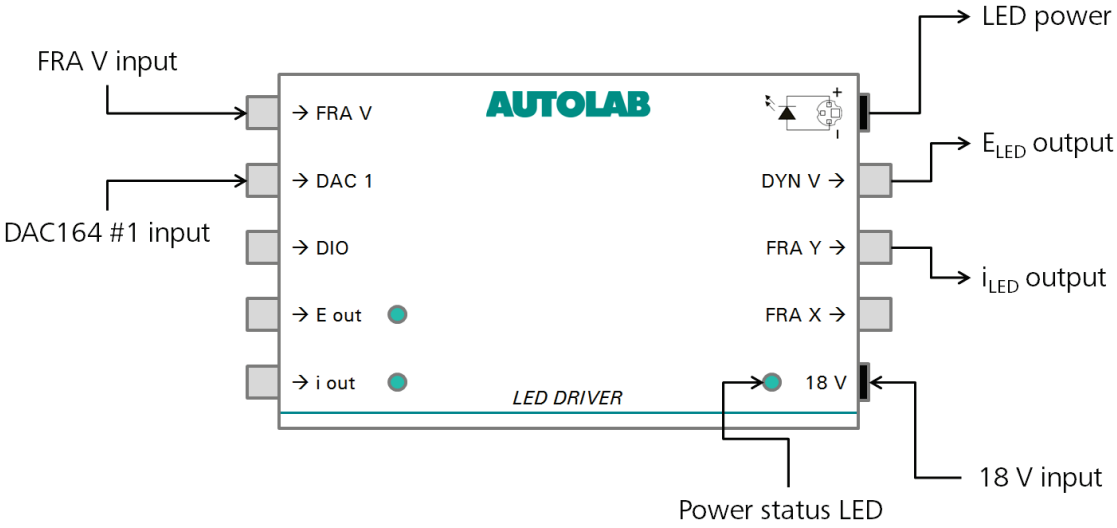


Figure 5 – Overview of the basic connections provided by the LED driver

The following connections are located on the left-hand side:

- **FRA V input (→ FRA V):** this input is used to supply the AC amplitude used to modulate the light intensity, in volts (0-10 V input range). See Section 4.3.2 for more information. When no signal is supplied to this input, this plug must be shorted using a 50 Ohm termination plug (included).
- **DAC164 #1 input (→ DAC 1):** this input is used to supply the DC amplitude used to modulate the light intensity, in volts (0-10 V input range). See section 4.3.1 for more information. This value must always be larger than the value supplied to the FRA V input.

The following basic connections are located on the right-hand side:

- **LED power (⇀):** this connector is used to provide current to the LEDs through a dedicated cable. This cable is used to interface the driver and the holder described in Section 4.2.
- **E_{LED} output (DYN V →):** this output provides a voltage (0-10 V), corresponding to the difference between the value provided to the DAC1 input and the value provided to the FRA V input (on the left-hand side of the driver).
- **i_{LED} output (FRA Y →):** this output provides a voltage (0-1 V), proportional to the LED current. The output value, in mV, corresponds to the driving current, in mA (1000 mV → 1000 mA driving current). For IMPS and IMVS measurements, this output is fed into the FRA Y input.
- **18 V input:** this input is used to supply power the LED driver. The driver is powered when the power status LED located next to this input is lit.

4.1.2 – Optional connections

Figure 6 shows an overview of the optional connections to and from the LED driver (the basic connections are grayed out). All the connectors located on the left-hand side of the driver are input connections from the Autolab PGSTAT to the LED driver. The BNC connectors located on the right-hand side of the driver are the output connections to the Autolab PGSTAT.

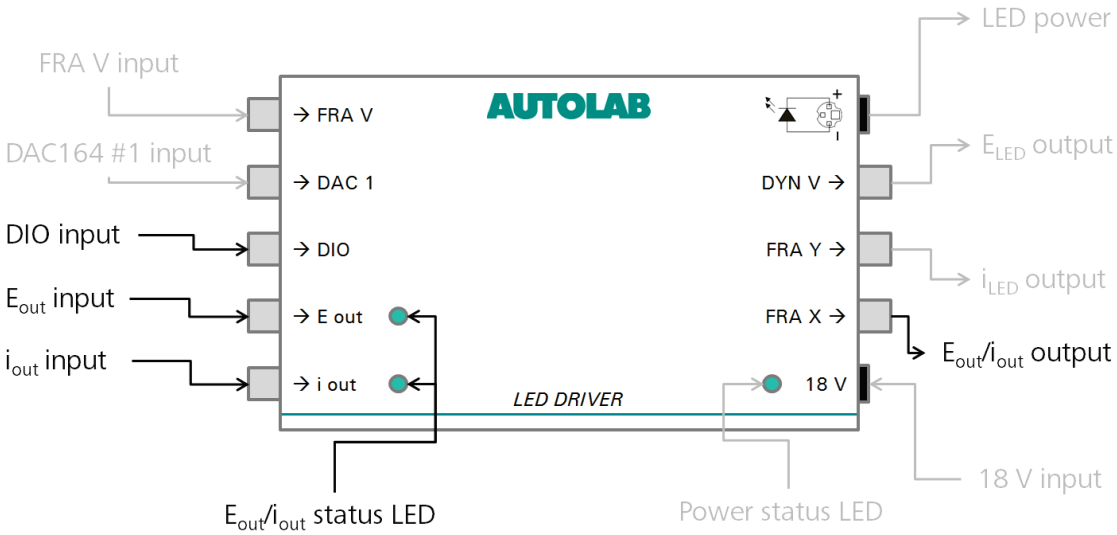


Figure 6 – Overview of the optional connections provided on the LED Driver (Basic connections are greyed out)

The following connections are located on the left-hand side:

- **DIO input (→ DIO):** this input can be used to connect to the DIO port(s) of the Autolab. By setting the DIO to the down status (default) or the up

status, the switch connected to the E_{out} and i_{out} can be toggled[2]. The default position is set to i_{out}.

- **E_{out} input (→ E out):** this input can be used to connect to the E_{out} plug provided by the monitor cable of the Autolab (see Section 8.4.1 for more information). The E_{out} signal is required during IMVS measurements.
- **i_{out} input (→ i out):** this input can be used to connect to the i_{out} plug provided by the monitor cable of the Autolab (see Section 8.4.2 for more information). The i_{out} signal is required during IMPS measurements.

The following optional connections are located on the right-hand side:

- **E_{out}/i_{out} output (FRA X →):** this connector provides a direct connection to either the E_{out} or the i_{out} supplied on the left-hand side of the driver, through the E_{out} and i_{out} connectors, respectively. The default is i_{out} (indicated by the status LED). This output is connected to the FRA X for IMPS (i_{out}) or IMVS (E_{out}) measurements.

4.2 – Autolab LED array

The Autolab LED driver can be connected to a dedicated LED array. This array consists of a tri-focal LED assembly, collimated into a narrow beam with a lens. The LED array and the lens are enclosed in an anodized aluminium cover (see Figure 7).

The light beam width is 18°.

Warning

The lens mounted on the light source provided a highly focused beam of light. Do not look directly into the light source when it is operating, even if the driving current is small.

[2] The switch can also be toggled through an analog voltage. Supplying more than 2.5 V on this DIO input triggers the switch.

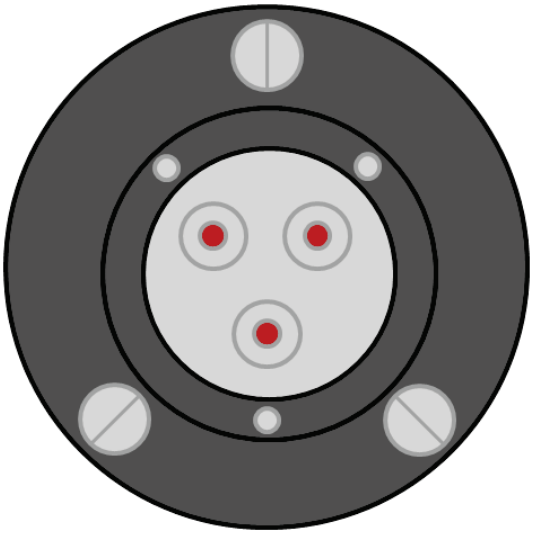


Figure 7 – Schematic top view of the LED array casing

The factory default cover, supplied with the kit, is fitted with three, 700 mA rated, red LEDs (wavelength: 627 nm).

Other covers are available, on request. The following wavelengths are available (see Table 1):

Article code	Color	Wavelength (nm)	Maximum output (Lumen)
LDC655	Deep Red	655	n.a.[3]
LDC627	Red	627	306
LDC617	Red-Orange	617	366
LDC590	Amber	590	396
LDC530	Green	530	390
LDC505	Cyan	505	360
LDC470	Blue	470	174
LDCCW	White (Cool)	n.a.	540
LDCWW	White (Warm)	n.a.	690
LDCNW	White (Neutral)	n.a.	330

Table 1 – Overview of the available LED covers

The back plane of the LED cover is fitted with two holes used to provide electrical contact to the LEDs enclosed in the cover (see Figure 8). Three screws are embedded into the cover to fasten it to the holder.

[3] The output in Lumen for the Deep Red source is not specified. The maximum output power is 1740 mW at 700 mA driving current.

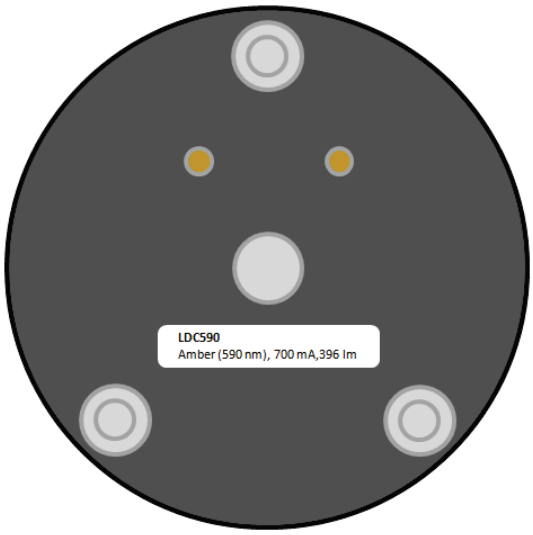


Figure 8 – Schematic bottom view of the LED array casing

A label is located on the back of the cover, indicating the type of LED included in the cover.

The cover can be mounted on a dedicated holder (see Figure 9). The holder is fitted with two spring mounted pogo pins that are intended to provide the electrical contact to the LEDs through the matching holes located in the back plane of the cover.

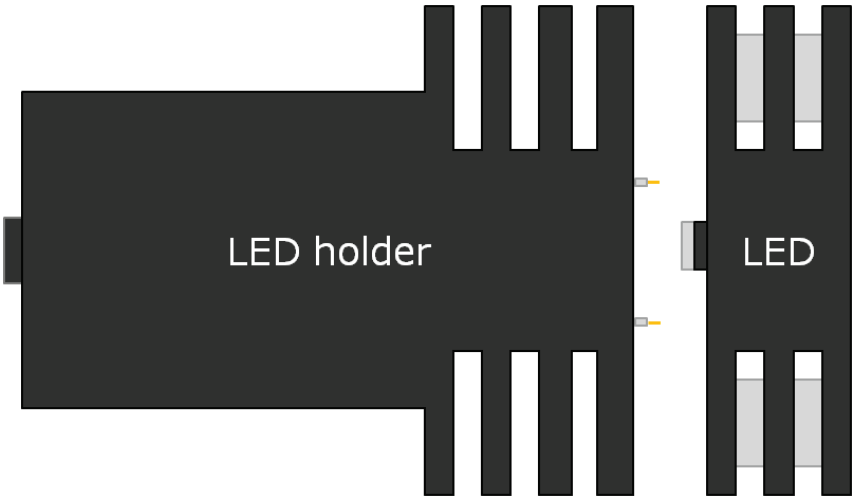


Figure 9 – The LED cover and the holder

To attach the cover to the holder, align the pogo pins with the matching holes in the back plane of the cover. The three screws located in the cover can be used to tighten the cover onto the holder.

Note

When tightening these screws, do not tighten one screw at a time but alternate between both screws in order to distribute the traction on each screw evenly. Do not over tighten the screws.

No soldering is required. Connecting the LEDs through pogo pins allows for a quick change of the wavelength of the light source, by simply replacing one cover by another.

Warning

Do not exchange the LED cover while the driver is in operation. Always power off the LED Driver before exchanging the LED cover.

The LED cover and the holder are fitted with six radial cooling fins, which allow evacuation of the heat generated by the light source. The higher the light intensity or the driving current supplied to the LEDs by the LED driver, the hotter the holder becomes (see Figure 10).

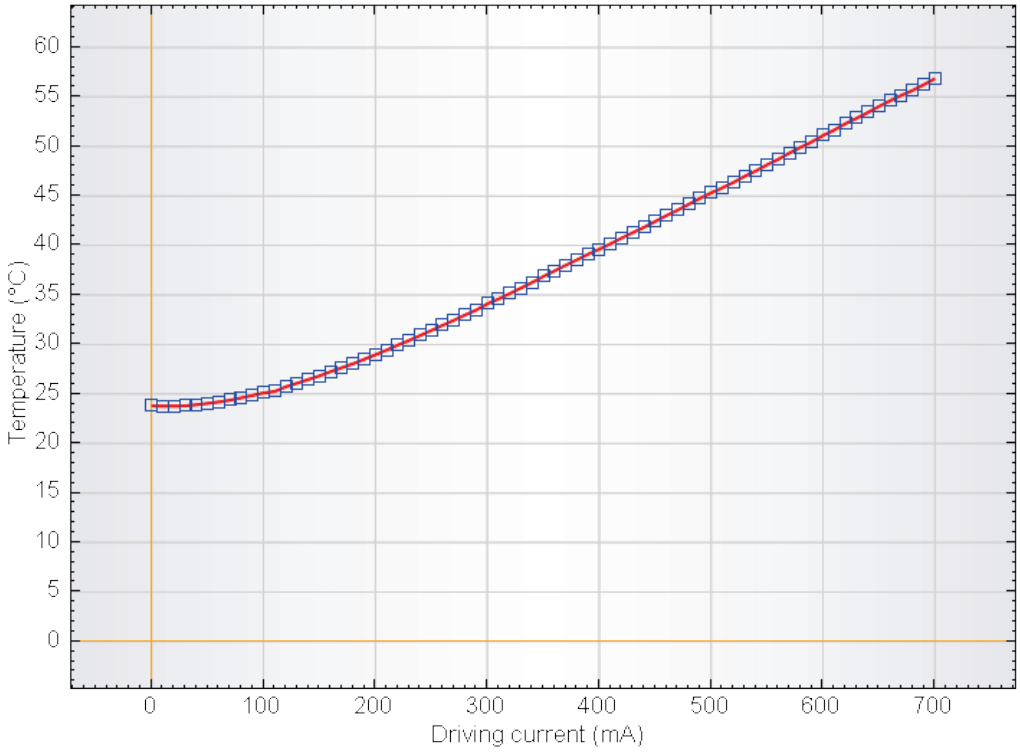


Figure 10 – Surface temperature of the LED cover in function of the driving current, in mA (measured with a 590 nm Amber LED cover, settling time: 60 s)

Warning

When the light source is driven at high currents, the cooling fins can get very hot (up to 60 °C). Do not touch these fins and allow for enough cooling time to prevent injury.

Figure 11 shows the cover attached to the holder.

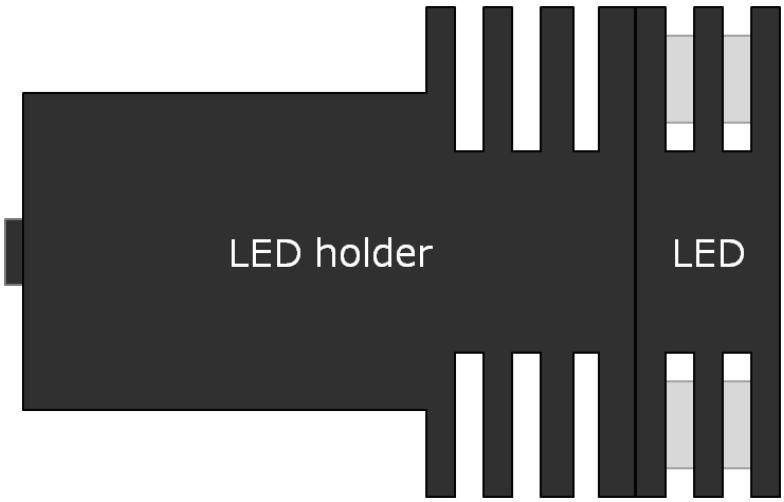


Figure 11 – The complete LED cover holder

4.3 – Autolab connections for light intensity control

Depending on the experimental setup, two connection schemes are possible between the LED driver and the Autolab:

- **Measurements at constant light illumination:** these measurements are performed with the LED driver set to a fixed user-defined light intensity. The light source intensity can be changed during the experiment, but no additional modulation is used. For this setup, only the DAC 1 input of the driver is used. The → FRA V input **must be** shorted by a 50 Ohm terminator plug (see Section 4.3.1 for more information).
- **Measurements at modulated light illumination:** these measurements are performed with the LED driver set to a fixed user-defined light intensity with an additional low amplitude intensity modulation. For these measurements, the DAC 1 and FRA V inputs are both connected to the Autolab while the E_{out}, i_{out} and DIO inputs can be connected to the Autolab, if necessary (see Section 4.3.2 for more information).

4.3.1 – Connections for constant illumination measurements

Figure 12 shows the overview of the connections to the LED driver required to set the light intensity to a constant, non modulated value.

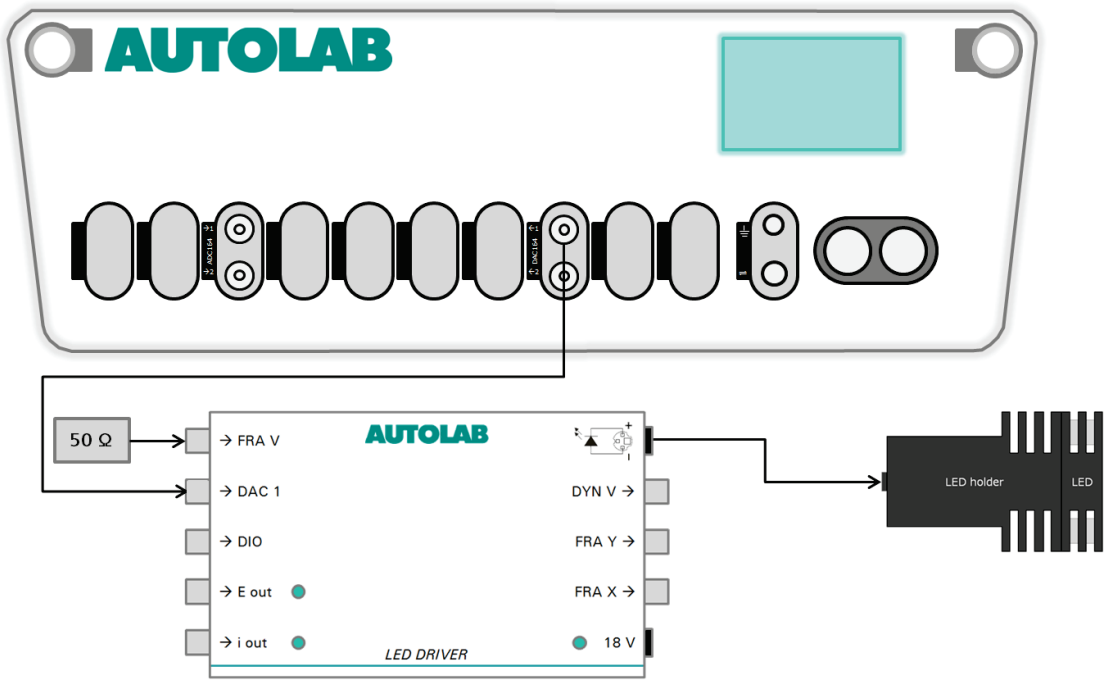


Figure 12 – Overview of the connections for constant illumination experiments

The FRA V input **must be shorted** when not in use with the provided 50 Ohm termination plug (see Figure 13).

Figure 13 – A 50 ohm terminator plug must be used to short the → FRA V input when this input is not used

Make sure that the 50 Ohm plug is connected to the → FRA V input at all times!

Note

If a FRA2 or FRA32M module is present, it is possible to replace the 50 Ohm terminator plug by a BNC or SMB cable from the ← V connector on the front panel of the FRA module and the → FRA V input.

The light intensity of the LED array is controlled by setting the driving current (passing through the LED power plug on the right-hand side). This driving current is defined by setting the DAC164 #1 output to a value between 0 and 10 V.

This voltage value is converted by the LED driver to a constant current using the following relationship:

$$i_{LED} = \left(\frac{i_{Range}}{V_{Range}} V_{DAC164}\right) = \left(\frac{1000\ mA}{10\ V} V_{DAC164}\right) = 100\ mA/V \cdot V_{DAC164}$$

Where i_{LED} is the output driving current, in mA, i_{Range} is the current range of the LED driver (1000 mA by default), V_{Range} is the input range of the LED driver (10 V) and V_{DAC164} is the output value of the DAC164 #1, in V.

Using the factory default values, setting the V_{DAC164} to 1 V will result in a driving current, i_{LED} of 100 mA. Setting the V_{DAC164} to 0 V switches the light off and setting the V_{DAC164} to 10 V will generate the maximum light intensity.

Warning

Do not use DAC164 #2 to control the light intensity. The channel is internally connected to the PGSTAT and is not suitable for this application.

Warning

Do not look directly into the light generated by the LED array.

4.3.2 – Connections for modulated illumination measurements

To modulate the light intensity, the → FRA V input is now connected to the front panel output of the FRA module. The sinewave generated by the FRA module is used to modulate the output of the LED Driver using a sinewave current superimposed on the DC driving current.

Note

The maximum modulation frequency is **20 kHz**.

For the FRA2 module, the ← V BNC plug can be connected to the → FRA V input of the LED driver, as shown in Figure 14, using the provided SMB to BNC adaptor plugs.

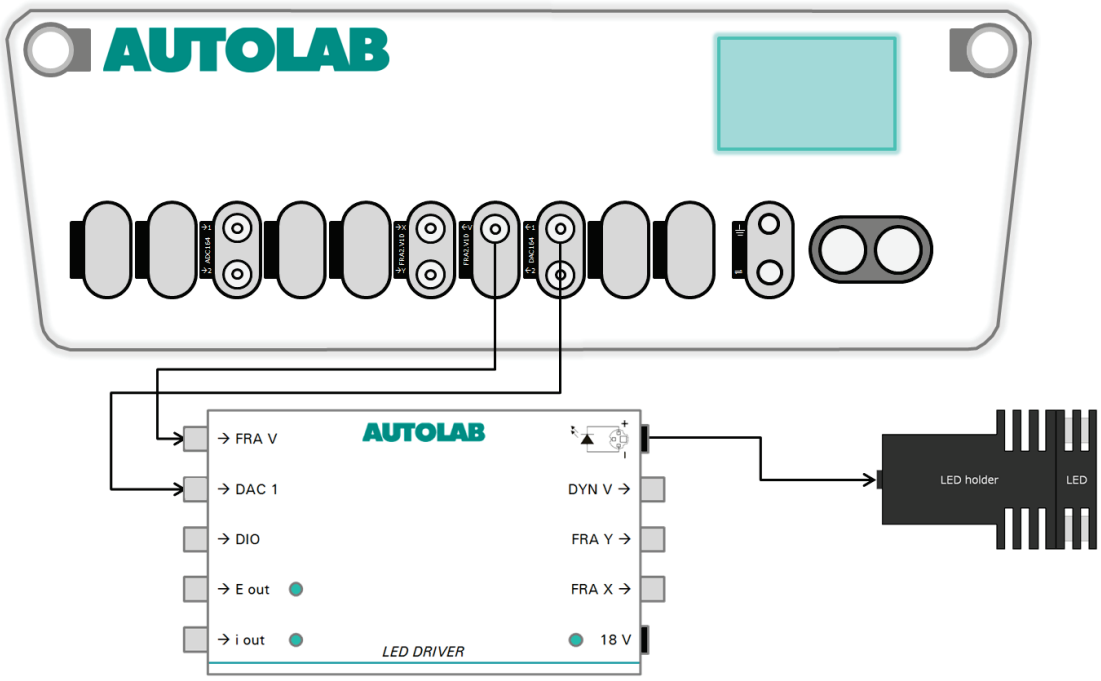


Figure 14 – Overview of the connections for modulated illumination experiments (FRA2)

The FRA32M module ← V SMB plug can be connected to the → FRA V input of the LED driver, as shown in Figure 15, using the provided SMB to BNC adaptor plug.

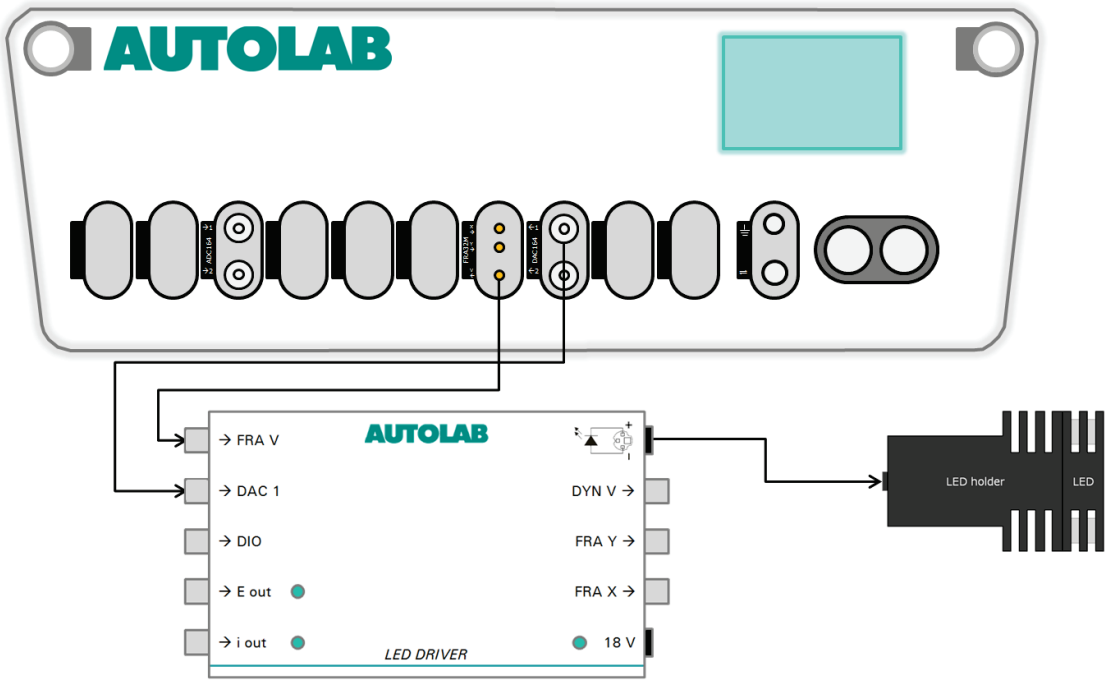


Figure 15 – Overview of the connections for modulated illumination experiments (FRA32M)

The light intensity of the LED array is controlled by setting the driving current (passing through the LED power plug on the right-hand side). This driving current is defined by setting the DAC164 #1 output to a value between 0 and 10 V and by setting the amplitude of the FRA V output to a value between 0 and 0.35 V (RMS).

The difference between the DAC164 output and the FRA V output is converted by the LED driver to a modulated current using the following relationship:

$$i_{LED} = i_{DC} - i_{AC} = \left(\frac{i_{Range}}{V_{Range}} (V_{DAC164} - V_{FRA\,V}) \right)$$

$$i_{LED} = 100\ mA/V \cdot (V_{DAC164} - V_{FRA\,V})$$

Where i_{LED} is the output driving current, in mA, i_{Range} is the current range of the LED driver (1000 mA by default), V_{Range} is the input range of the LED driver (10 V), V_{DAC164} is the output value of the DAC164 #1, in V and $V_{FRA\,V}$ is the output value of the FRA V, in V.

Warning

The V_{DAC164} value must always be larger than $V_{FRA\,V}$ so that the $V_{DAC164} - V_{FRA\,V}$ difference is always positive. When this difference is negative, the net output driving current i_{LED} is 0 mA, regardless of the values of V_{DAC164} and $V_{FRA\,V}$.

Note

The output driving current, i_{LED} is given by the difference between the constant current, i_{DC} and the modulated current, i_{AC}.

Using the factory default values, setting the V_{DAC164} to 1 V and the $V_{FRA\,V}$ to 0.1 V will result in a DC driving current, i_{DC} of 100 mA, modulated by an AC current, i_{AC} of 10 mA. Setting the $V_{DAC164} - V_{FRA\,V}$ to 0 V switches the light off and setting the $V_{DAC164} - V_{FRA\,V}$ to 10 V will generate the maximum light intensity.

Warning

Do not use DAC164 #2 to control the light intensity. The channel is internally connected to the PGSTAT and is not suitable for this application.

Warning

Do not look directly into the light generated by the LED array.

4.3.3 – Optional connections

Additionally, a number of connections are available on the left and right hand side of the driver. These connections are not mandatory, but can be used to facilitate the measurement of experimental values used in IMPS and IMVS measurement. Figure 16 shows the overview of the optional connections between the Autolab and the LED driver. The connections shown in Figure 16 are complementary to the connections shown in Figure 16 (shown in grey in Figure 16).

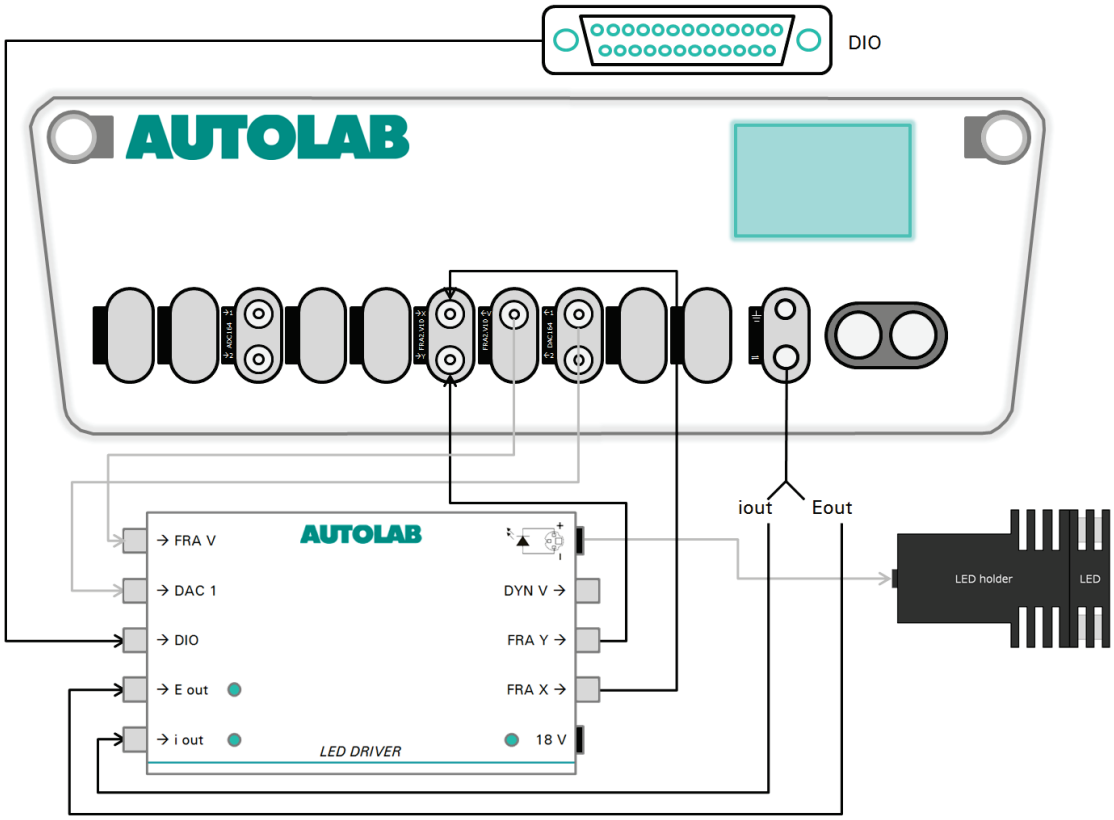


Figure 16 – Overview of the optional (black) connections for modulated light intensity experiments

The black connections shown in Figure 16 are optional and are provided for convenience sake. These connections are required for signal readout during IMVS and IMPS measurements. More information on these measurements can be found in Section 8.4.

The FRA Y → output located on the right-hand side of the LED driver can be used to feed the converted current to the → Y input of the FRA impedance analyzer.

The E_{out} and i_{out} inputs, located on the left-hand side of the driver can be connected to the corresponding outputs located on the monitor cable provided with the Autolab PGSTAT (see Figure 17).

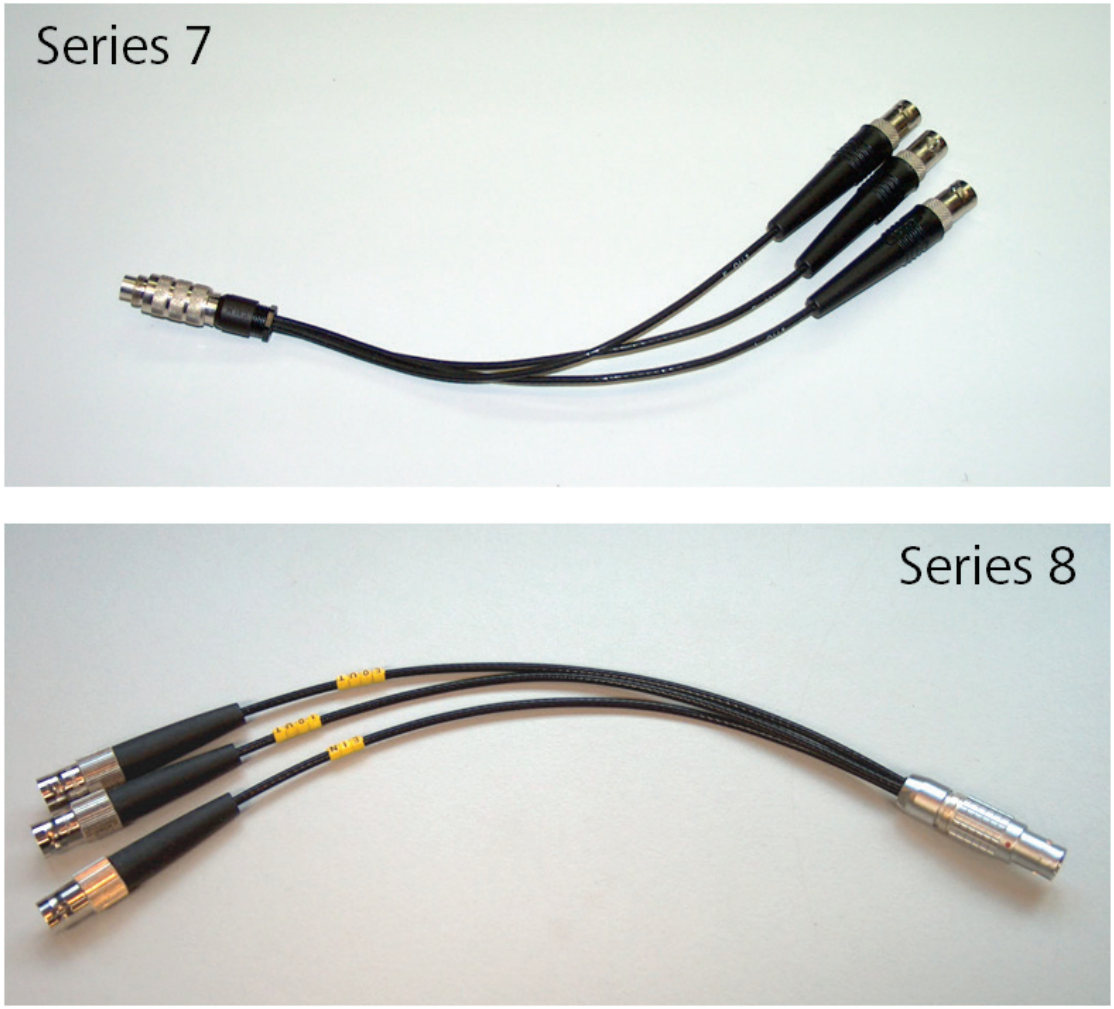


Figure 17 – Monitor cable for the series 7 PGSTAT (above) and the series 8 PGSTAT (below)

Note

The PGSTAT101 and M101 module are not supplied with a monitor cable. This cable must be ordered separately (article codes for PGSTAT101: **CABLE.MONITOR4**, M101: **CABLE.MONITOR.MAC**). Please contact Metrohm Autolab B.V. (info@metrohm-autolab.com) or your local distributor for more information.

The E_{out} and i_{out} outputs signals are used for the IMVS and IMPS, respectively. By feeding these two signals into the driver, the user can pass either one of these signals to the FRA X output located on the right-hand side of the driver, using the either one of the compatible DIO cables (see Figure 18).

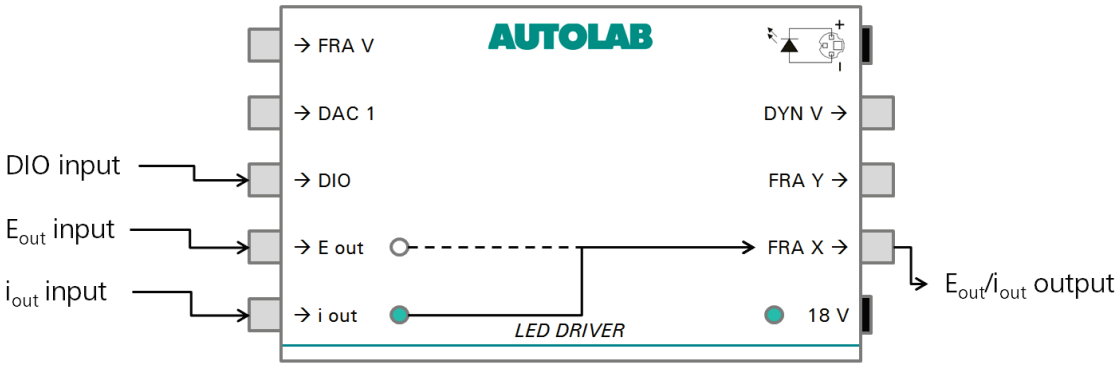


Figure 18 – Overview of the feedthrough connections for E_{out} and i_{out}

Two different DIO cables are compatible with the LED Driver:

- For all the supported Autolab Potentiostat/Galvanostat instruments, except the PGSTAT101 and the M101 module, a male DIN25 to female BNC cable is supplied with the LED Driver kit (see Figure 19). This cable can be connected to either P1 or P2 of the instrument. The female BNC connector can be connected to the → DIO connector on the LED Driver using the supplied 2 m long BNC cable.

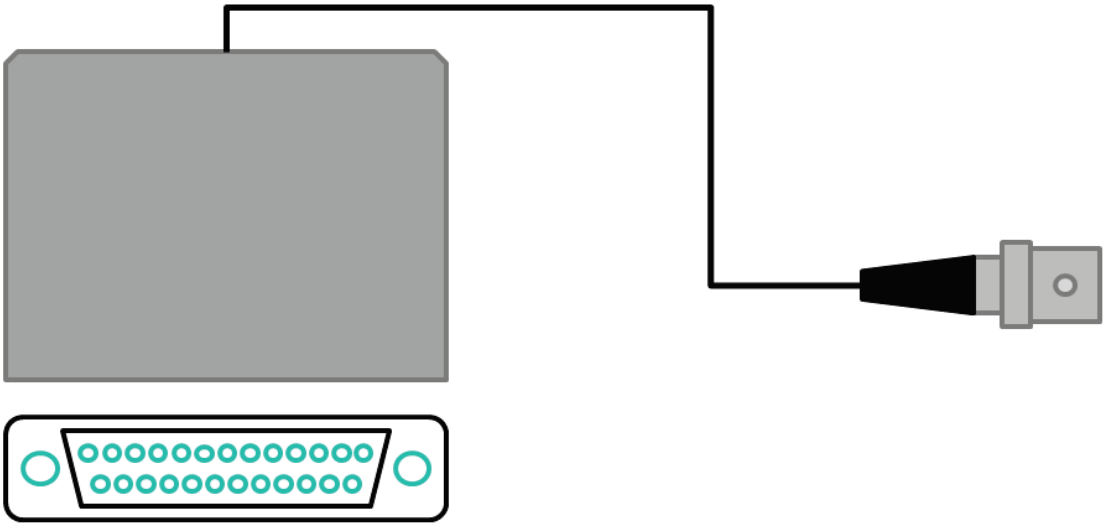


Figure 19 - DIO cable for the Series 7 and Series 8 PGSTAT instruments

- For the PGSTAT101 and the M101 module, a male DIN15 to female BNC cable is available (see Figure 20). This cable can be connected to the DIO port of the instrument or module. The female BNC connector can be connected to the → DIO connector on the LED Driver using the supplied 2 m long BNC cable.

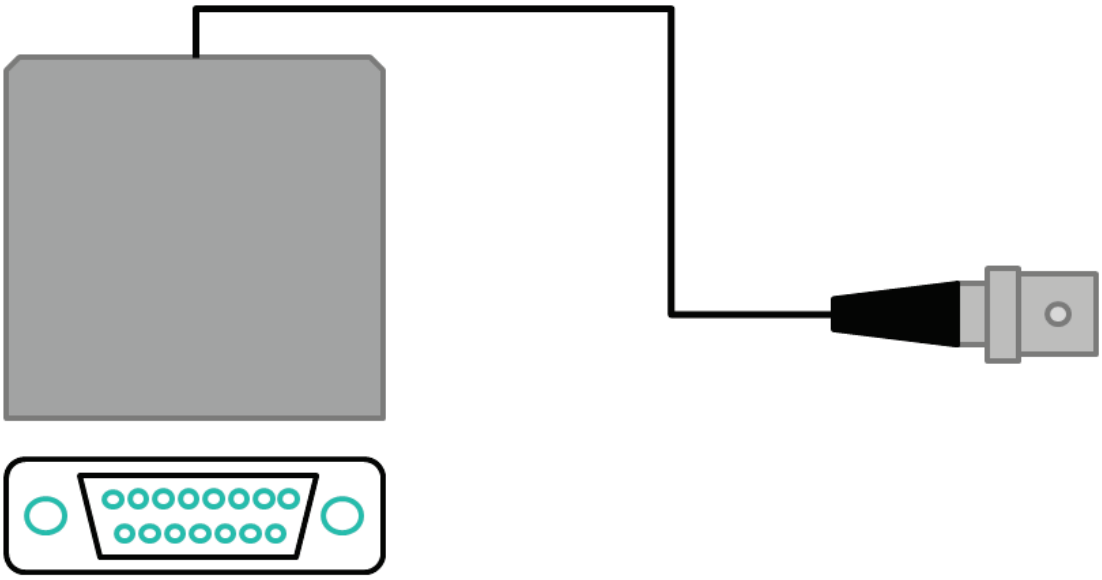


Figure 20 - DIO cable for the Autolab PGSTAT101/M101

By setting the DIO input to high or low[4], the switch located in the driver can be toggled remotely. The status LEDs located on the left-hand side of the driver will indicate the selected input (see Figure 21).

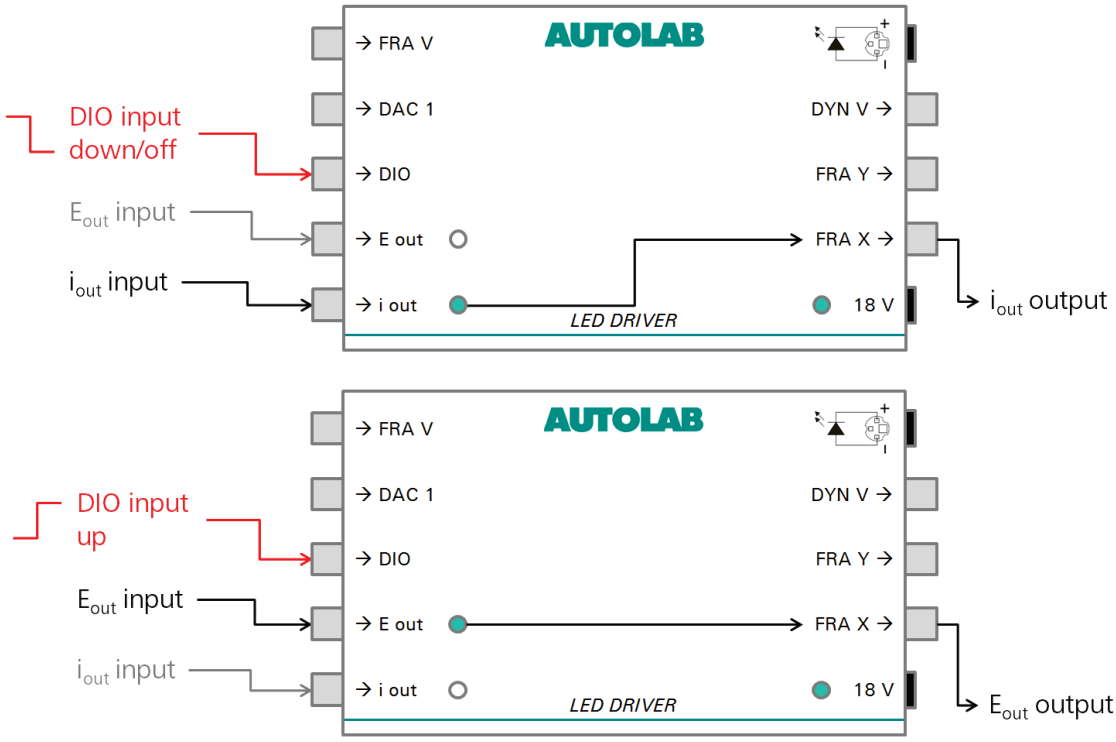


Figure 21 – The i_{out}/E_{out} switch can be set remotely through the DIO input (top, DIO status UP or disconnected – i_{out} selected, bottom, DIO status DOWN – E_{out} selected)

[4] Please refer to the External devices tutorial, available from the Help menu in NOVA for more information on the control of the DIO port(s) of the Autolab.

By default, when no connection to the DIO is present, the i_{out} is always selected, indicated by the status LED on the left-hand side. The switch can also be toggled through an analog voltage. Supplying more than 2.5 V on this DIO input triggers the switch.

Note

Using the built in E_{out}/i_{out} switch is not mandatory for IMVS/IMPS measurements, but is recommended because it facilitates the wiring schemes.

4.4 – Autolab connections to analog outputs

The Autolab LED Driver provides two analog outputs, labelled DYN V → and FRA Y →, respectively, on the right-hand side of the driver. These two outputs can be connected to the external inputs of the Autolab.

Depending on the output, the following values are provided:

- **DYN V →:** this output provides the potential difference between the → **DAC 1** input and the → **FRA V** input of the LED Driver, in volts. The output range is between 0 V and 10 V.
- **FRA Y →:** this output provides the value of the driving current passing through the LEDs, converted to voltage by a current-to-voltage converter. The current follower used in this circuit has a single current range of 1 A, with a 1 V/A conversion. The output range is between 0 V and 1 V.

Figure 22 shows the values recorded on the **DYN V →** plug in function of the specified driving current. A linear relationship is observed between the two values, and the measured slope corresponds to 0.01 V/mA.

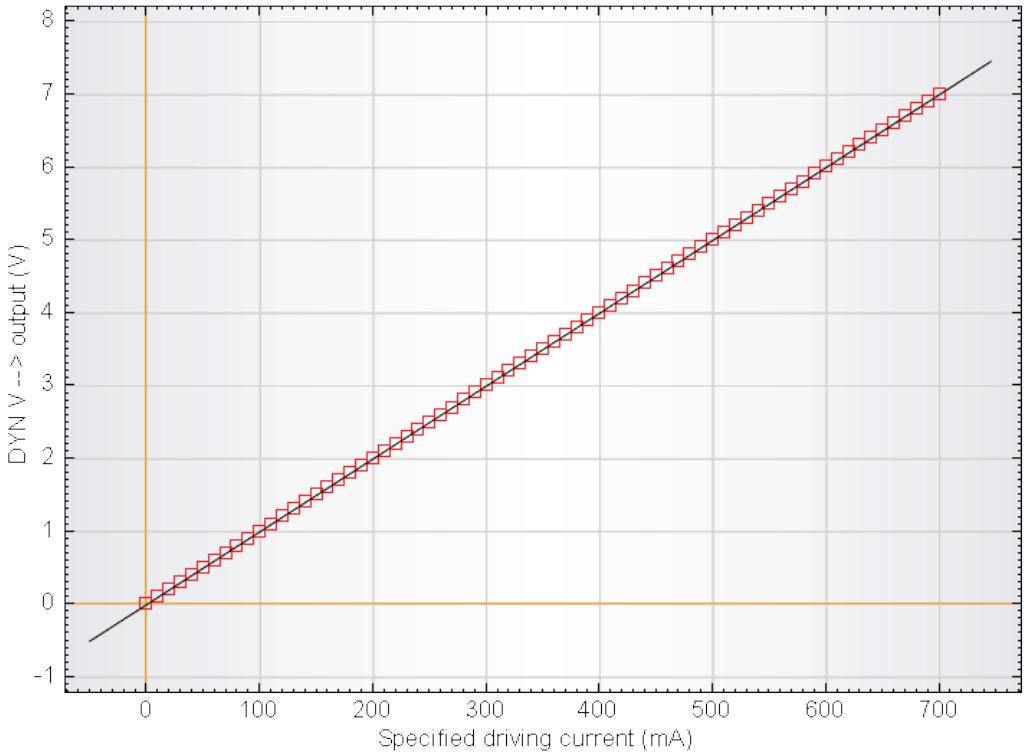


Figure 22 – Output value of the DYN V→ plug plotted against the specified driving current

Figure 23 shows the values recorded on the **FRA Y →** plug in function of the specified driving current. A linear relationship is observed between the two values, and the measured slope corresponds to 0.001 V/mA.

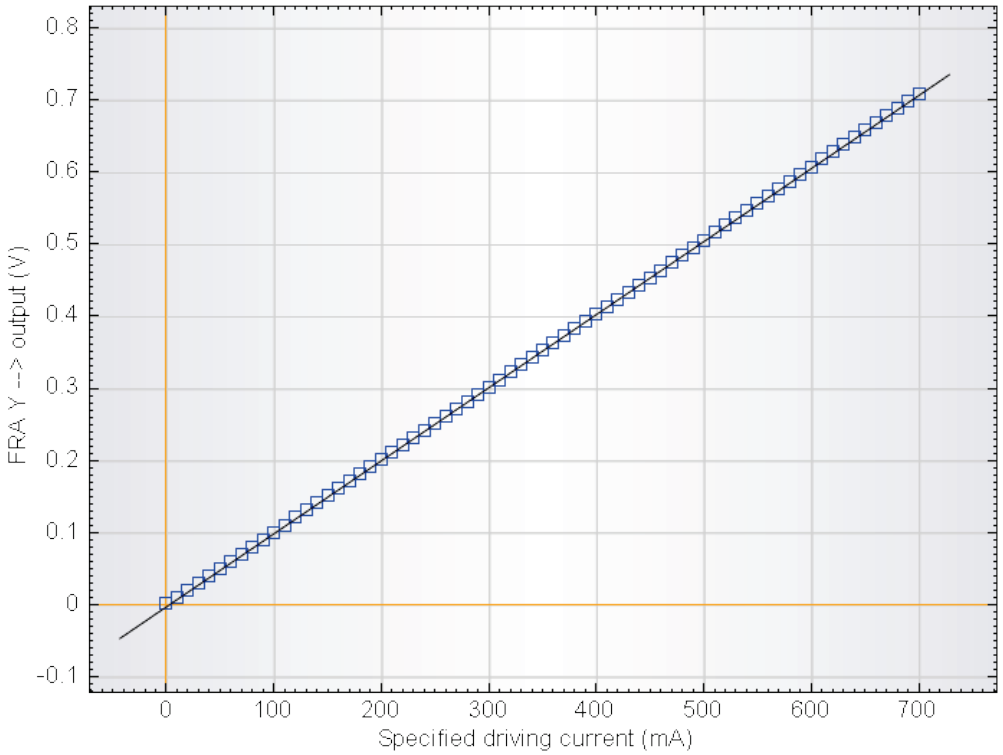


Figure 23 – Output value of the FRA Y → plug plotted against the specified driving current

5 – Software control

The Autolab LED driver is intended to be controlled by the NOVA software. The control of the driver is performed through the use of analog and/or digital settings:

- Analog control of the light intensity and modulation, if applicable.
- Digital control of the E_{out}/i_{out} through the DIO port.

This section provides details on the light intensity control.

5.1 – Analog control of the light intensity

Regardless of the type of experiment, the light intensity of the LED is controlled by supplying a voltage value between 0 V and 10 V to the DAC 1 input and the FRA V input of the driver. At all times, the value supplied to the FRA V input must be smaller than the value supplied to the DAC 1 input. The supplied voltage difference between the inputs is converted into a driving current, i_{LED} given by:

$$i_{LED} = i_{DC} - i_{AC} = \left(\frac{i_{Range}}{V_{Range}} (V_{DAC164} - V_{FRA\,V}) \right)$$

$$i_{LED} = 100\ mA/V \cdot (V_{DAC164} - V_{FRA\,V})$$

Or, when no voltage is supplied on the FRA V input (50 Ohm termination plug in place) by:

$$i_{LED} = \left(\frac{i_{Range}}{V_{Range}} V_{DAC164}\right)$$

$$i_{LED} = 100\ mA/V\ \cdot V_{DAC164}$$

Where i_{LED} is the output driving current, in mA, i_{Range} is the current range of the LED driver (1000 mA by default), V_{Range} is the input range of the LED driver (10 V), V_{DAC164} is the output value of the DAC164 #1, in V and $V_{FRA\,V}$ is the output value of the FRA V, in V.

Using the factory default values, setting the V_{DAC164} to 1 V and the $V_{FRA\,V}$ to 0.1 V will result in a DC driving current, i_{DC} of 100 mA, modulated by an AC current, i_{AC} of 10 mA. Setting the $V_{DAC164} - V_{FRA\,V}$ to 0 V switches the light off and setting the $V_{DAC164} - V_{FRA\,V}$ to 10 V will generate the maximum light intensity.

Note

When the input voltage is 90 mV or less, the current output will be switched off and the output current will be 0 mA. The minimum current is therefore limited to 9 mA.

5.1.1 – Settings for the DAC 1 input

The DAC 1 input of the LED driver controls the DC light intensity. This setting is defined in the software through the *Control external device (DAC)* command, available from the Measurement – general group of commands (see Figure 24).

Note

The *Control external device (DAC)* command is an Advanced command. Adjust the Profile in NOVA if necessary.

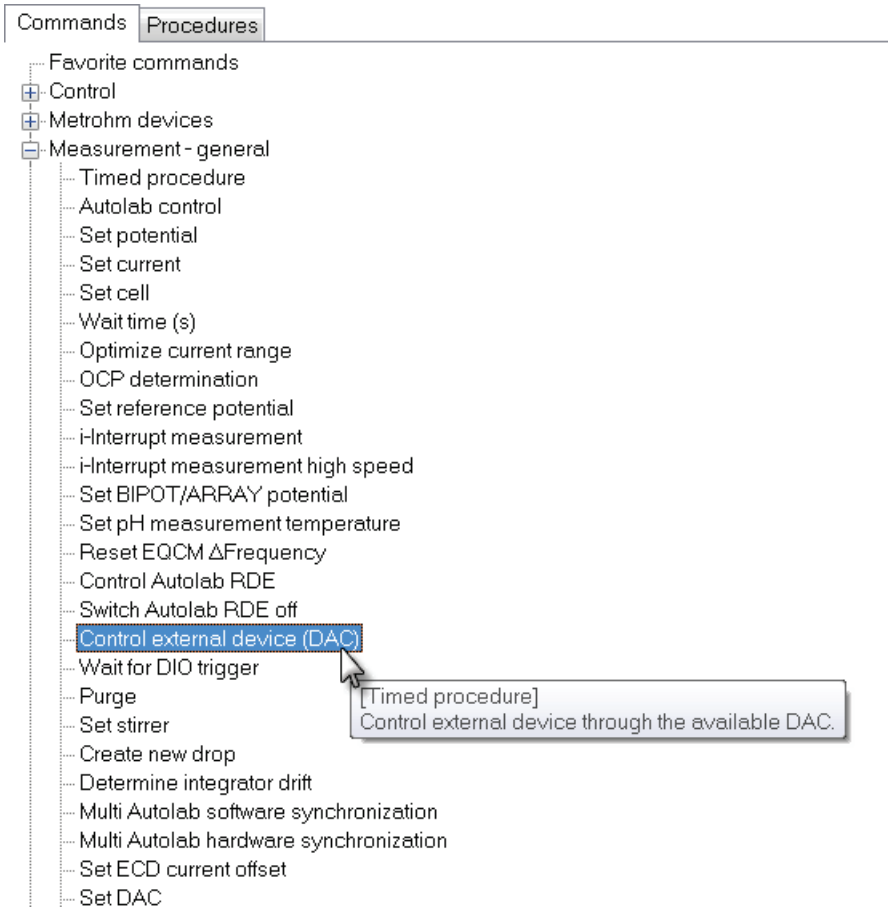


Figure 24 – The *Control external device (DAC)* command is used to set the DC light intensity

The *Control external device (DAC)* command is a Timed command, and as such must always be included in a *Timed procedure*. This command has the following parameters:

Parameter	Description
Set value	The converted value required to control the external device (the value corresponds to (*offset* + DAC voltage * *slope*)
DAC channel	The DAC channel used to control the external device (DAC 3, corresponding to DAC 1 on the front panel, should always be used)
Conversion offset	Defines the offset for the value conversion
Conversion slope	Defines the slope for the value conversion

For Autolab LED driver, the conversion offset should be set to 0 and the conversion slope should be set to (10 V/1000 mA) if the value should be defined in mA or to (10 V/1 A) if the value should be defined in A (see Figure 25).

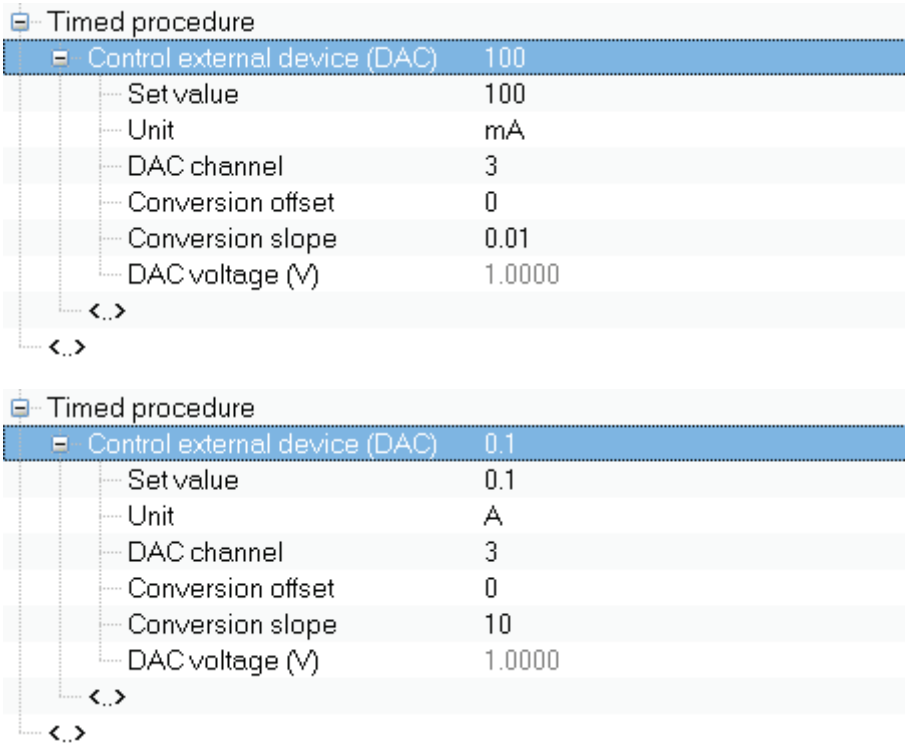


Figure 25 – The settings required for the *Control external device (DAC)* command (Top: defined in mA, Bottom: defined in A)

For bookkeeping purposes, it is convenient to rename the command and to indicate which units are used to set the light intensity. In the rest of this document, the V to mA conversion will be assumed (see Figure 26).

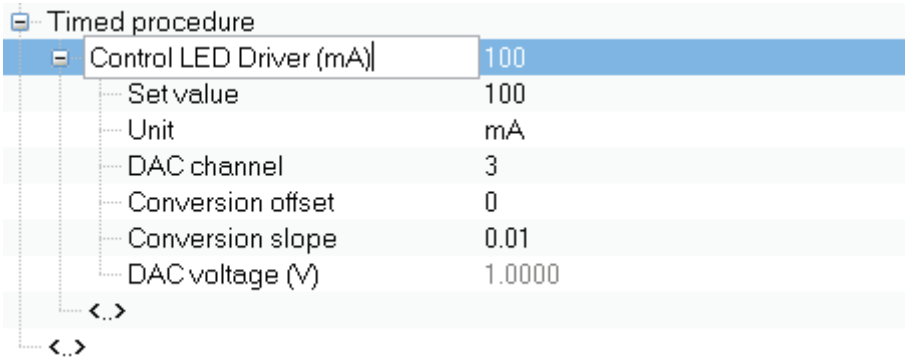


Figure 26 – Renaming the command (note the units)

Furthermore, it is recommended to save the modified command in the My commands database, by right-clicking the command and choosing the Save in My commands option (see Figure 27).

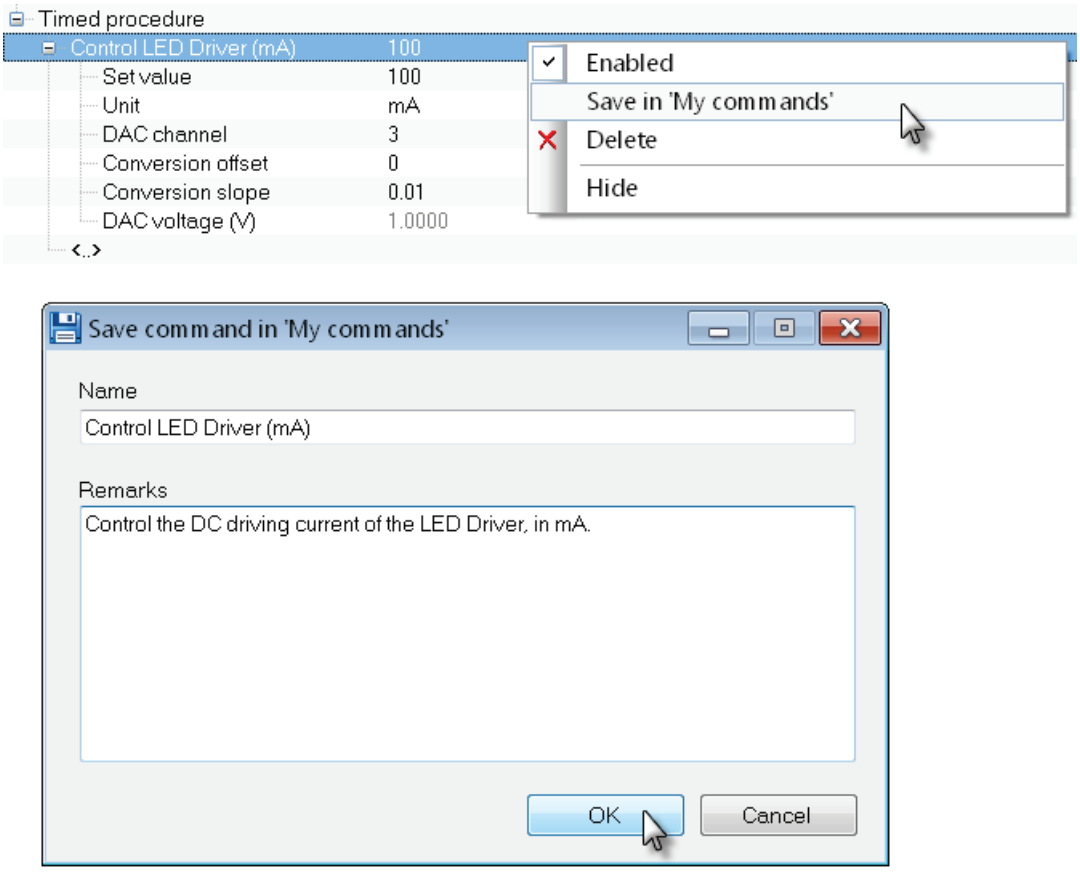


Figure 27 – Saving the command in the My commands database

The command will appear in the *My commands* group of commands. It can be used at any time in the procedure (see Figure 28).

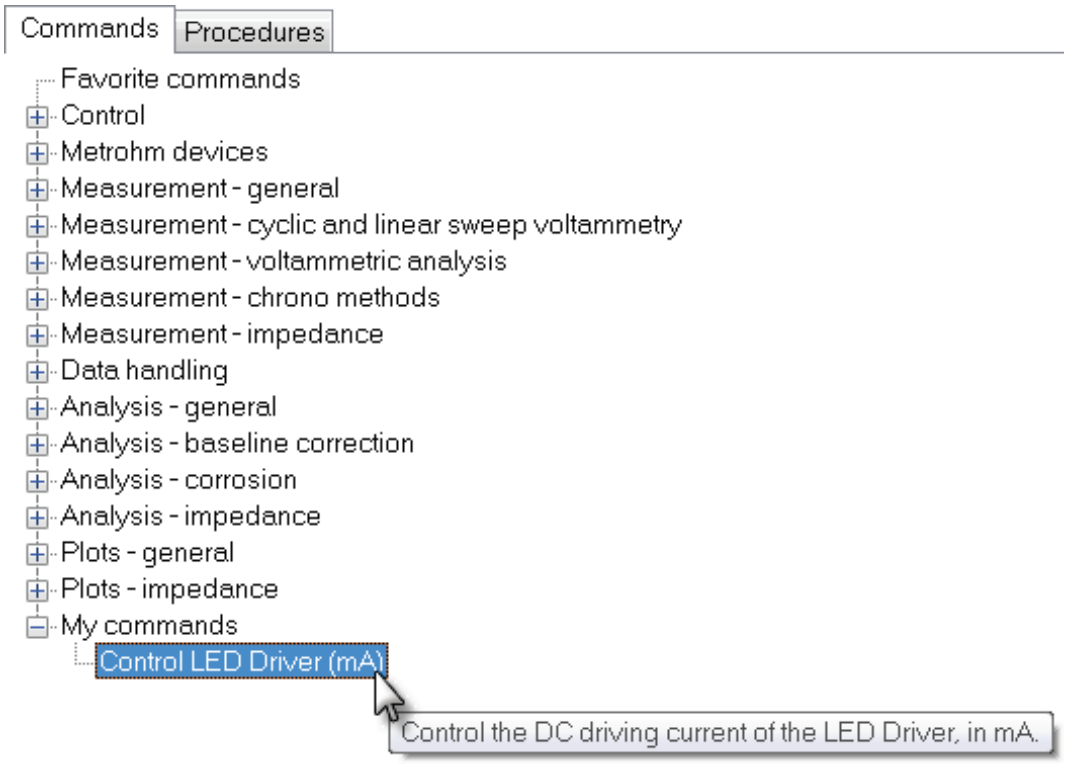


Figure 28 – The saved command is available in the My commands group

5.1.2 – Settings for the FRA V input

The FRA V input of the LED driver controls the AC light intensity modulation. This setting is defined in the software through the *FRA measurement external* command, available from the Measurement – impedance group of commands (see Figure 29).

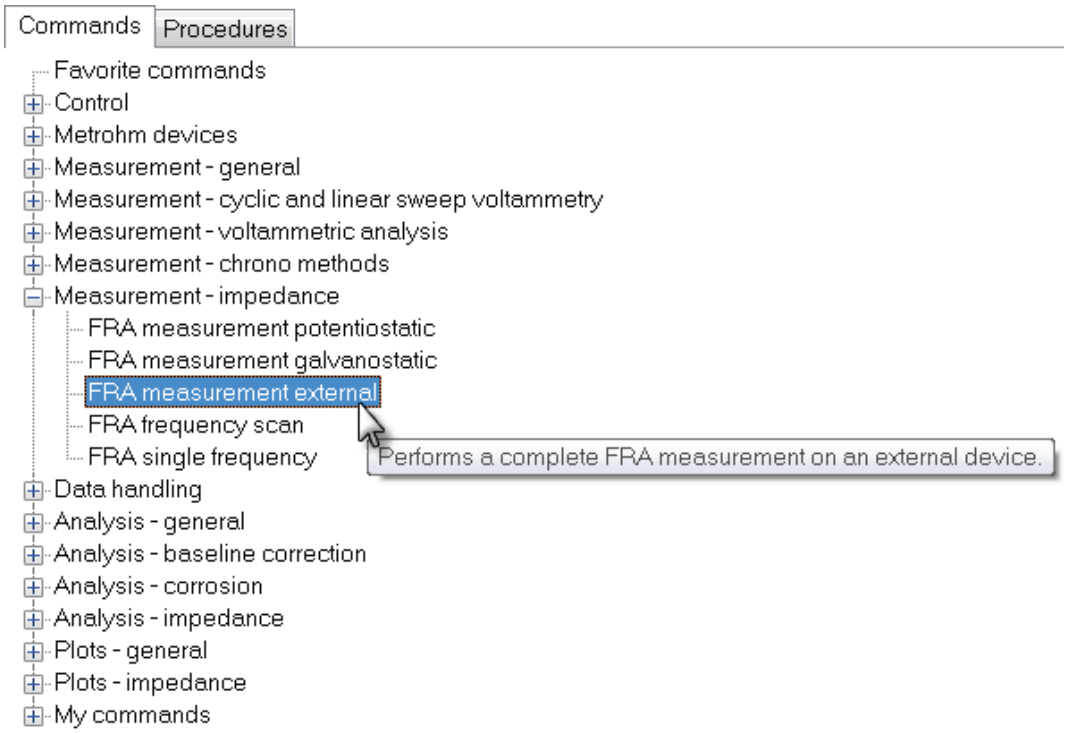


Figure 29 – The *FRA measurement external* command is used to modulate the light intensity

Note

When no modulation is required in the experiment, the FRA V input of the LED driver must be shunted using a 50 Ohm terminator plug (included, see page 18).

The *FRA measurement external* command is used to perform a FRA measurement using the external inputs and outputs of the FRA module. The output of the FRA module is used to generate a sinewave which is fed into the LED Drive FRA V input. This sinewave, supplied as a voltage (0 – 5 V top amplitude range) is converted into an AC driving current.

The *FRA measurement external* command is a composite command (see Figure 30).

Note

The *FRA measurement external* command is an Advanced command. Adjust the Profile in NOVA if necessary.

Figure 30 – The commands and parameters of the *FRA measurement external* command

The settings for controlling the light source modulation are defined in the FRA sampler. To edit these settings, click the … button located next to the FRA sampler in the FRA single frequency command (see Figure 31).

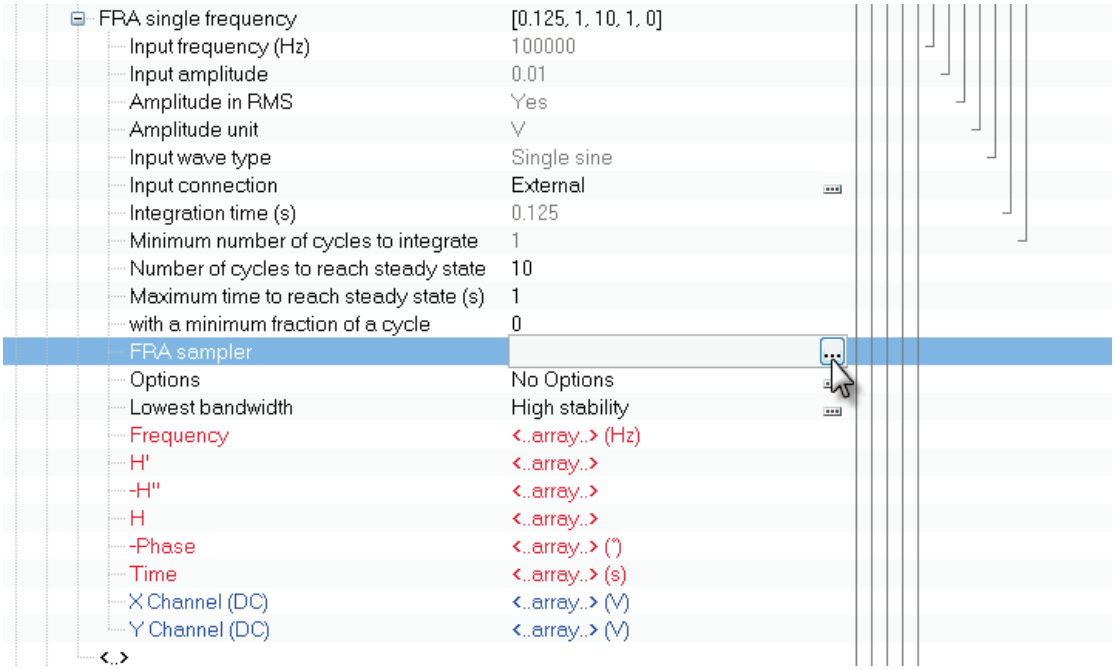


Figure 31 – The settings required for light source modulation are defined in the FRA sampler

The FRA sampler window will be displayed (see Figure 32).

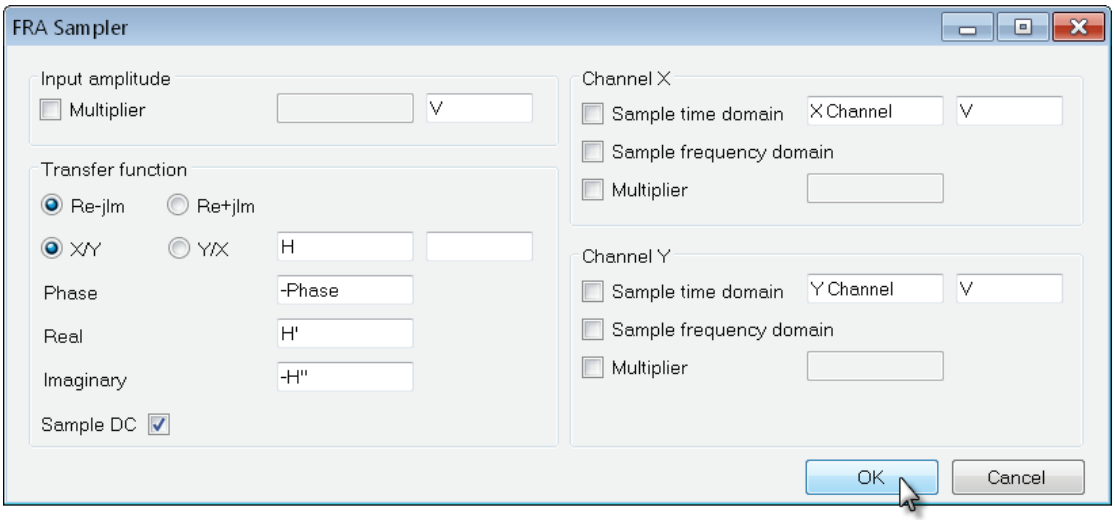


Figure 32 – The FRA sampler window

The FRA sampler window is used to define the settings for the generation of the sinewave and the analysis of the transfer function. To control the modulation of the LED directly in AC driving current, the **Input amplitude** multiplier must be specified properly.

Click the Multiplier checkbox in the top left corner and specify the conversion factor required to convert the supplied voltage into driving current (10 V/1000 mA). In the units field indicate the units used for this converted AC signal (see Figure 33).

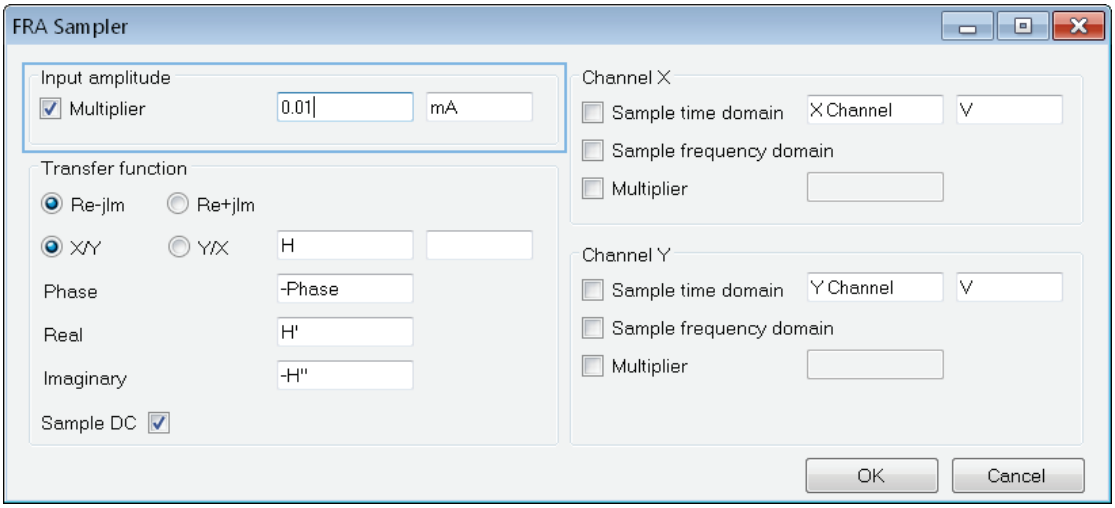


Figure 33 – The settings required for the input amplitude

Note

In the example shown in Figure 34, the conversion settings are defined in such way that the amplitude can be defined as AC driving current in mA. If the AC unit is to be defined in A, the conversion factor needs to be adjusted (to 10, see page 30 for more information).

The settings for the transfer function, defined in the Channel X and Channel Y sections of the FRA Sampler depend on the type of measurement. More information is provided in Sections 8.4.1.1 and 8.4.2.1.

Press the OK button to close the FRA sampler.

The applied light modulation can now be specified in the *FRA frequency scan* command. Click the ... button located next to the *FRA frequency scan* command to open the FRA frequency scan editor window (see Figure 34).

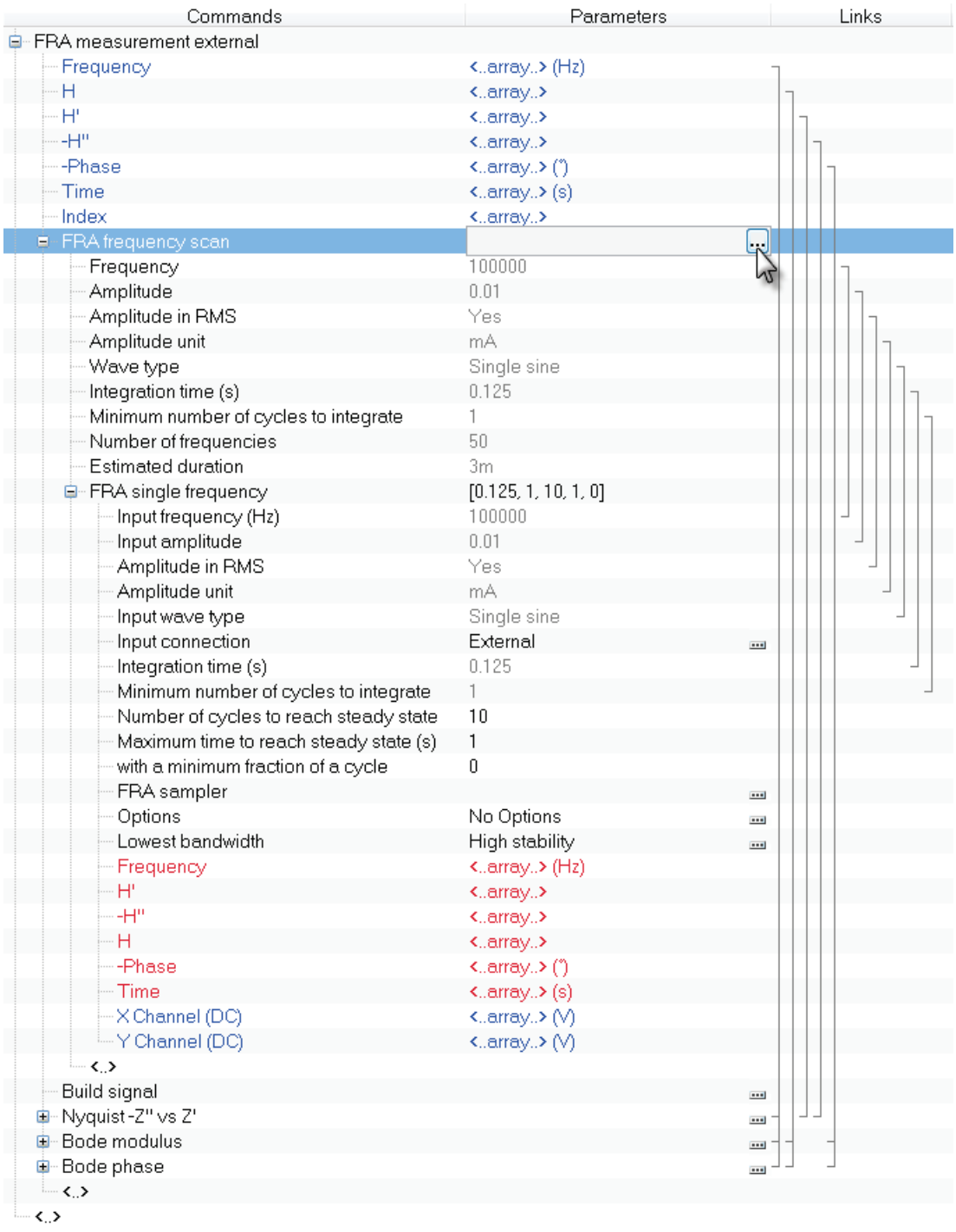


Figure 34 – Opening the frequency editor

The FRA frequency scan editor window will be displayed (see Figure 35).

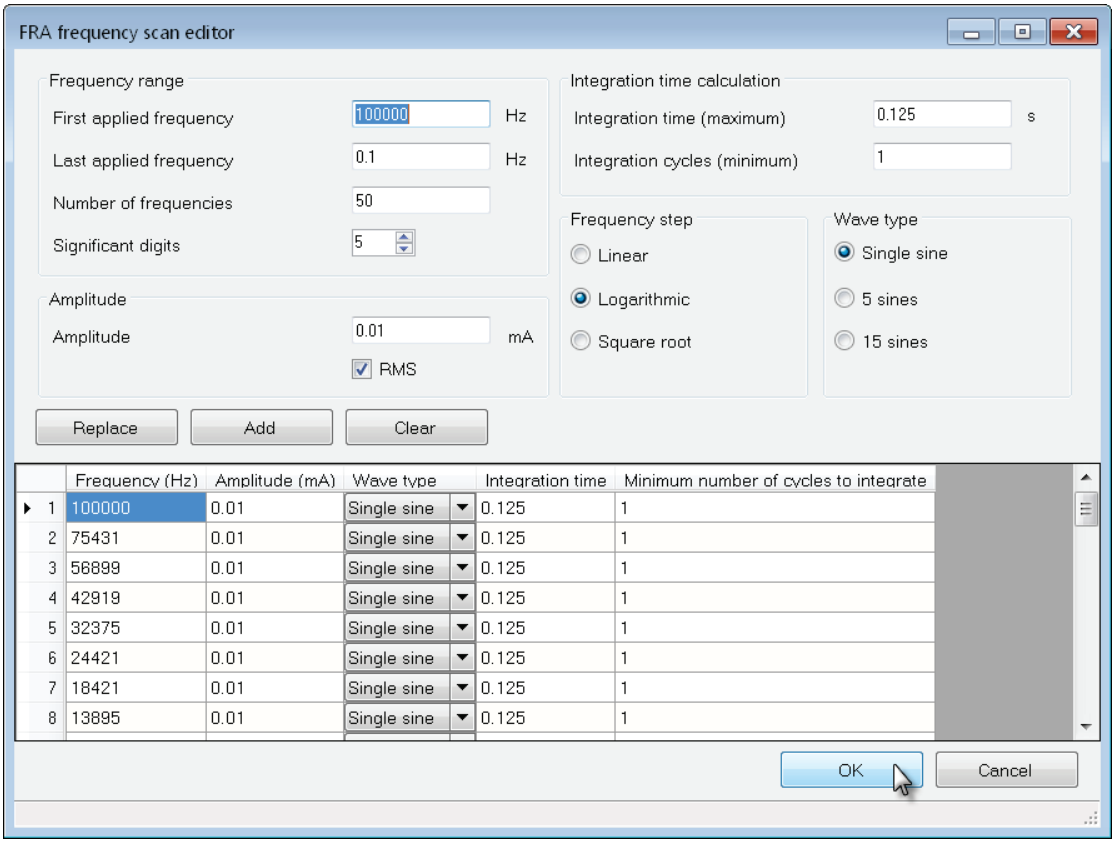


Figure 35 – The FRA frequency scan editor window

The units of the amplitude are indicated in the FRA frequency editor window. In this example, the conversion factor defined in Figure 33 specified that the units of the amplitude are mA.

The maximum amplitude, $i_{AC}(MAX)$, that can be specified is 350 mA (RMS) or 500 mA (TOP). However, for the default LED covers supplied by Metrohm Autolab, the total driving current cannot exceed the maximum limit of 700 mA. The applied amplitude must also be larger than the DC driving current, at all time.

$$0\ mA \leq i_{total} = i_{DC} + i_{AC}(TOP) \leq 700\ mA$$

5.1.3 – Settings for the DIO control

The → DIO BNC connector can be used to switch remotely between the → E out or →i out inputs on the LED Driver, using the DIO port(s) provided by the Autolab, as explained in Section 4.3.3.

To control the DIO of the Autolab, the *Autolab control* command[5] must be used to initialize the DIO port used in the experiment (not required for the PGSTAT101 and the M101 module). The DIO port used must be initialized at the beginning of the procedure.

Note

Pin #1, located on DIO port A is used to control the switch.

To initialize the DIO port A, located on either P1 or P2, the direction setting for this port must be set to Output, using the drop-down list provided in the Autolab control window (see Figure 36).

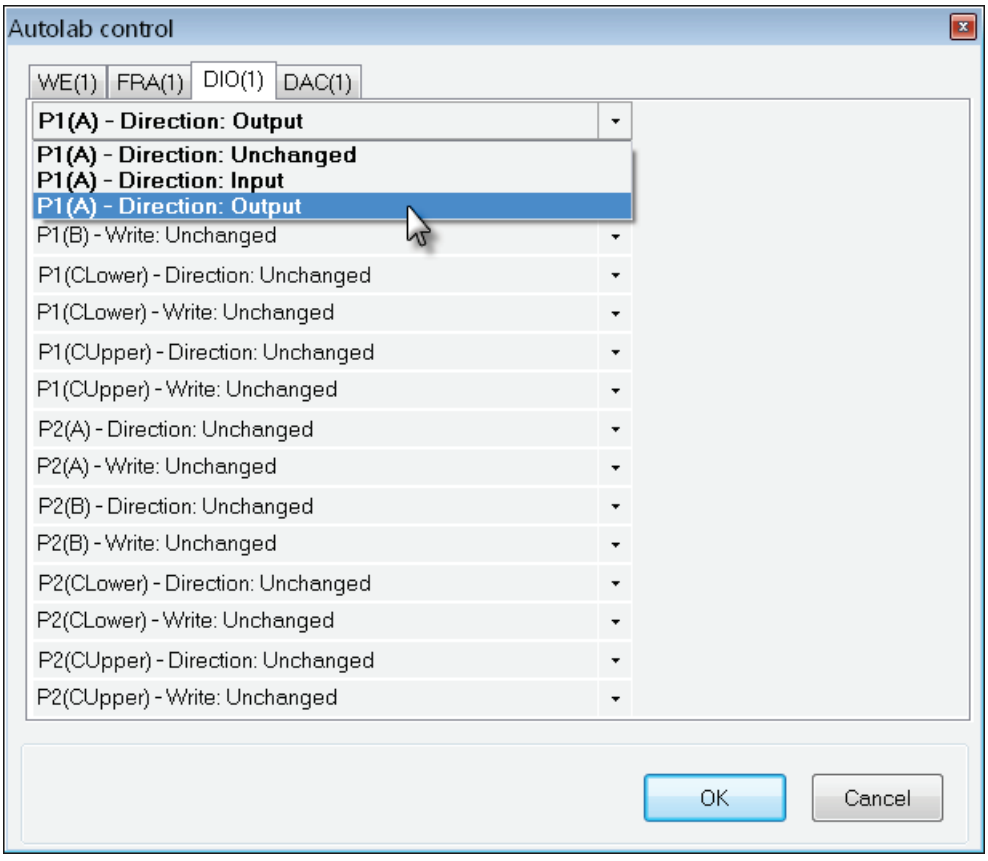


Figure 36 – Setting the direction of Port A of connector P1 to Output

[5] More information on the settings of the DIO ports can be found in the External devices tutorial. More information on the Autolab control command can be found in the Autolab control turorial. Both tutorials can be found in the Help menu of NOVA.

After the port is initialized, the status of Pin #1 can be set at any time to high (5 V) or low (0 V), using the *Autolab control* command.

- **Low (00000000 – 0):** when pin #1 is set to low status (0 V), the → E out input is active. This is also the default status when nothing is connected to the → DIO input of the LED Driver.
- **High (00000001 – 1):** when pin #1 is set to high (5 V), the → i out input is active. The switch will be kept in this position as long as pin #1 is set to high.

The status of pin #1 of the initialized port can be changed at any time using the Autolab control window. The status can be set as a decimal value (0 or 1), or as a binary string (00000000 or 00000001). The status defined is permanent until changed (see Figure 37).

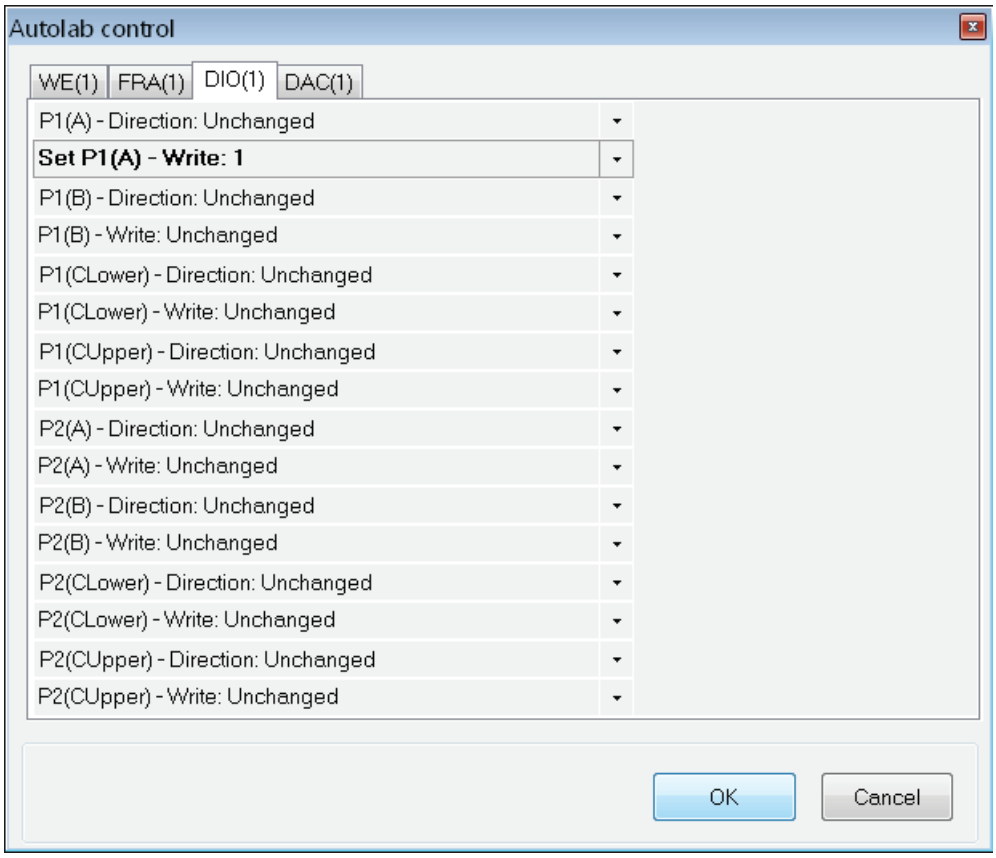


Figure 37 – Setting the status of pin #1

For the PGSTAT101 or M101 module, the same settings are used. However, in this case, only a single port is available (see Figure 38). Port A of the DIO connector of the PGSTAT101 or M101 does not have to be initialized since it is hardwired to output.

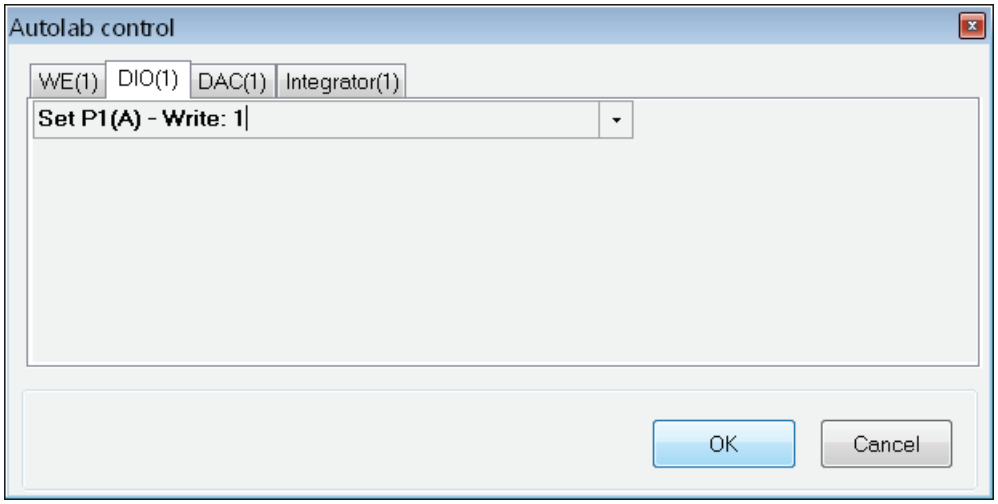


Figure 38 – Setting the status of pin #1 for the PGSTAT101 or M101 module

6 – Light source calibration

Quantitative results can only be obtained after the calibration of the light source. This can be done by using a calibrated photodiode exposed to the light source at a controlled distance on the optical bench. The calibration can be performed with the Autolab or with external digital multimeters. In this manual, the procedure used in combination with the Autolab is described.

The LED Driver kit is supplied with a calibrated photodiode, embedded into a cylindrical holder (see Figure 39). The measurement range of the photodiode is from 350 nm to 1100 nm.

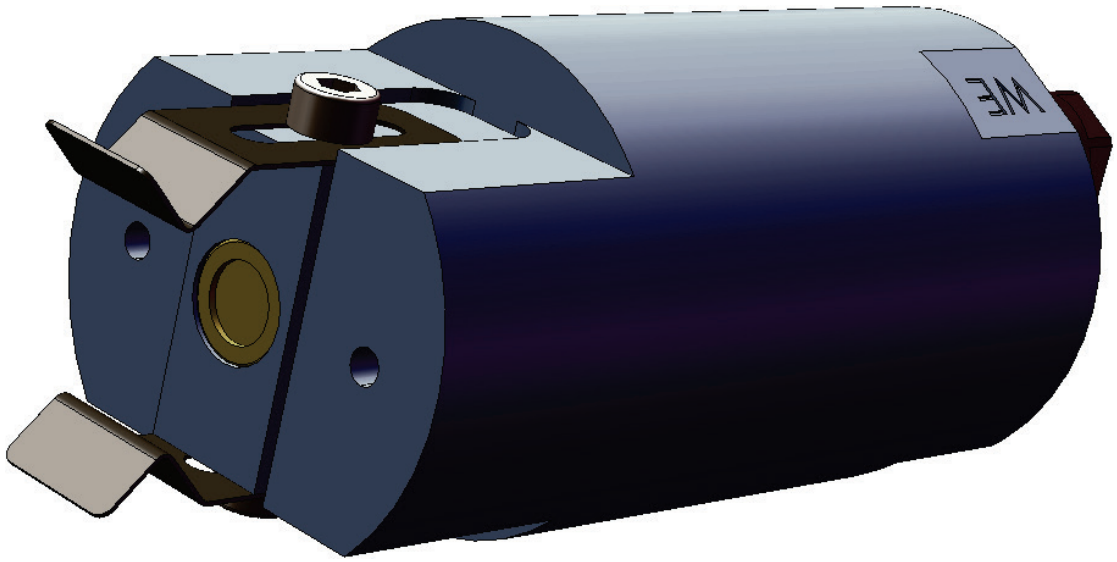


Figure 39 – The photodiode holder (front view)

The photodiode holder is fitted with three female 4 mm banana connectors, labeled WE (red), CE (black) and GND (green), respectively. These connectors are used to accommodate the cell connectors provided by the Autolab PGSTAT (see Figure 40).

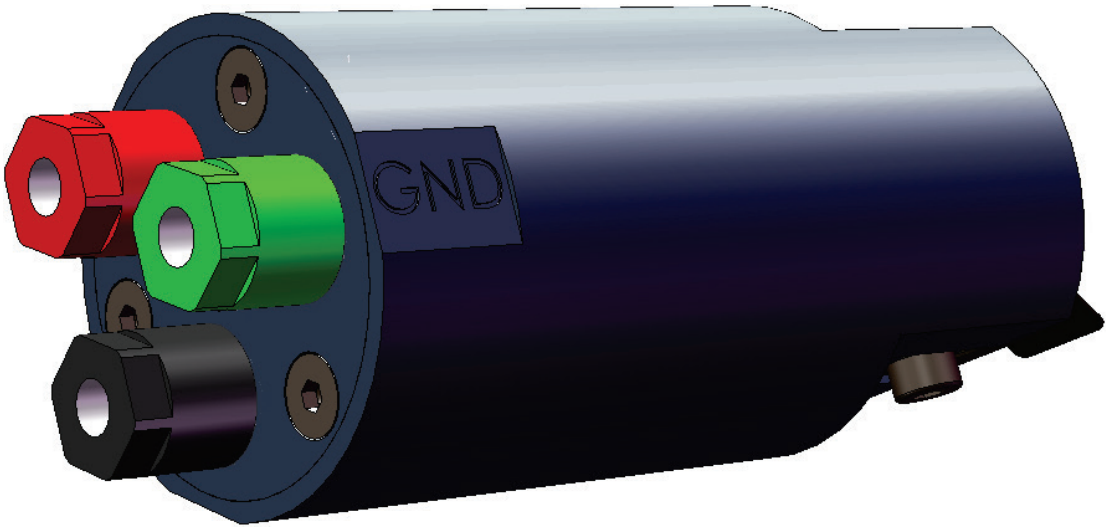


Figure 40 – The photodiode holder (back view)

The photodiode holder is also supplied with an additional plastic cover which can be mounted on top of the calibrated photodiode. This cover is designed to hold a filter[6] to protect the photodiode from exposure to light intensities beyond the damage threshold.

Warning

The photodiode will be irreversibly damaged when exposed to a light intensity of 100 mW/cm^2 or more. For very high intensity measurements, a neutral density filter may be required. Please contact your Metrohm Autolab distributor for more information.

The calibration procedure requires the calibrated photodiode to be placed at the required distance from the light source and to expose the photodiode to different light intensities (controlled by the driving current supplied by the LED Driver). The photodiode current can be converted to light intensity using the conversion values reported in the calibration certificate of the calibrated photodiode supplied with the LED Driver kit (see Figure 41).

[6] To protect the photodiode a reflective neutral density filter can be used. The size of the filter is 1.27 cm (1/2 inch).

Test Report

Model	FDS100-CAL	**Temperature**	25,0°C	**Test Date**	8-Jun-11
Serial No	11060821	**Humidity**	35%	**Tester**	Alexandra Ressel
Scan	CAL1				

λ [nm]	η [A/W]	λ [nm]	η [A/W]	λ [nm]	η [A/W]	λ [nm]	η [A/W]	λ [nm]	η [A/W]	λ [nm]	η [A/W]
350	6,95E-02	720	4,24E-01	1090	1,72E-01						
360	6,59E-02	730	4,35E-01	1100	1,37E-01						
370	6,38E-02	740	4,45E-01								
380	6,67E-02	750	4,56E-01								
390	7,27E-02	760	4,66E-01								
400	8,08E-02	770	4,76E-01								
410	9,02E-02	780	4,86E-01								
420	1,00E-01	790	4,96E-01								
430	1,10E-01	800	5,06E-01								
440	1,21E-01	810	5,16E-01								
450	1,31E-01	820	5,26E-01								
460	1,42E-01	830	5,35E-01								
470	1,52E-01	840	5,43E-01								
480	1,62E-01	850	5,52E-01								
490	1,72E-01	860	5,60E-01								
500	1,82E-01	870	5,68E-01								
510	1,93E-01	880	5,75E-01								
520	2,03E-01	890	5,83E-01								
530	2,14E-01	900	5,91E-01								
540	2,25E-01	910	5,99E-01								
550	2,35E-01	920	6,06E-01								
560	2,46E-01	930	6,13E-01								
570	2,58E-01	940	6,19E-01								
580	2,68E-01	950	6,25E-01								
590	2,79E-01	960	6,33E-01								
600	2,91E-01	970	6,36E-01								
610	3,02E-01	980	6,36E-01								
620	3,13E-01	990	6,31E-01								
630	3,24E-01	1000	6,22E-01								
640	3,35E-01	1010	6,04E-01								
650	3,47E-01	1020	5,73E-01								
660	3,57E-01	1030	5,28E-01								
670	3,70E-01	1040	4,68E-01								
680	3,81E-01	1050	3,99E-01								
690	3,92E-01	1060	3,23E-01								
700	4,03E-01	1070	2,59E-01								
710	4,14E-01	1080	2,12E-01								

Figure 41 – Calibration data provided on the calibration certificate

The calibration certificate provides a table of wavelengths (λ, in nm) and responsivity (η, in A/W). The responsivity values are reported in absolute values and should be normalized with respect to the active surface area of the photodiode (13 mm²).

Using this strategy, it is relatively easy to establish a driving current-to-light intensity correlation, as shown in Figure 42. The data shown in this plot was obtained at a distance of 20 cm, using a 590 nm LED cover (Amber).

The light intensity, P_{LED}, is calculated from the measured photodiode current, i_{SC}^{φ}, divided by the surface of the photodiode (0.13 cm²) and divided by the responsivity reported in the calibration certificate (see Figure 41).

$$P_{LED} = \left(\frac{i_{SC}^{\varphi}}{A \cdot \eta}\right) = \left(\frac{i_{SC}^{\varphi}}{0.13\ cm^2 \cdot 0.279\ A/W}\right)$$

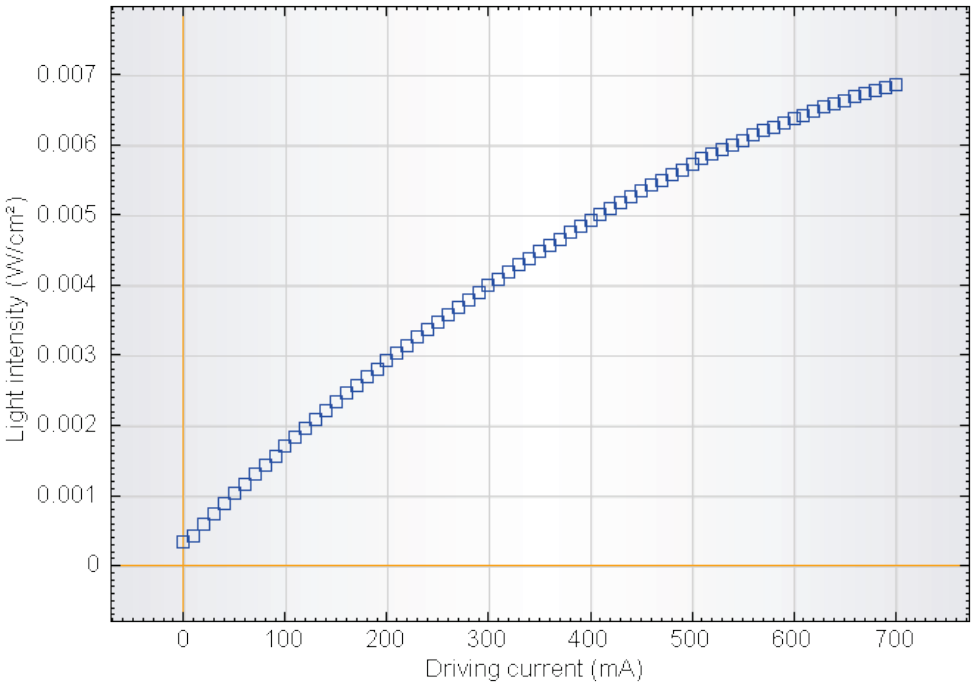


Figure 42 – Driving current to light intensity conversion curve, measured at 590 nm (Amber)

To use the photodiode, connect the RE/CE leads from the PGSTAT to the CE plug on the photodiode holder and connect the WE/S to the WE plug on the photodiode holder. Connect the green ground plug embedded in the cell cables of the Autolab to the matching GND banana connector of the photodiode holder.

Note

The photodiode current must be measured at short-circuit conditions (0 V applied) and at known wavelength.

7 – Cell holder

The calibrated photodiode holder is fitted with two sliding clamps that can be used to fix the cell onto the holder, provided that the cell is small enough to fit in this space. This holder is designed for a common form factor for experimental solar cells, like the one shown in Figure 42.

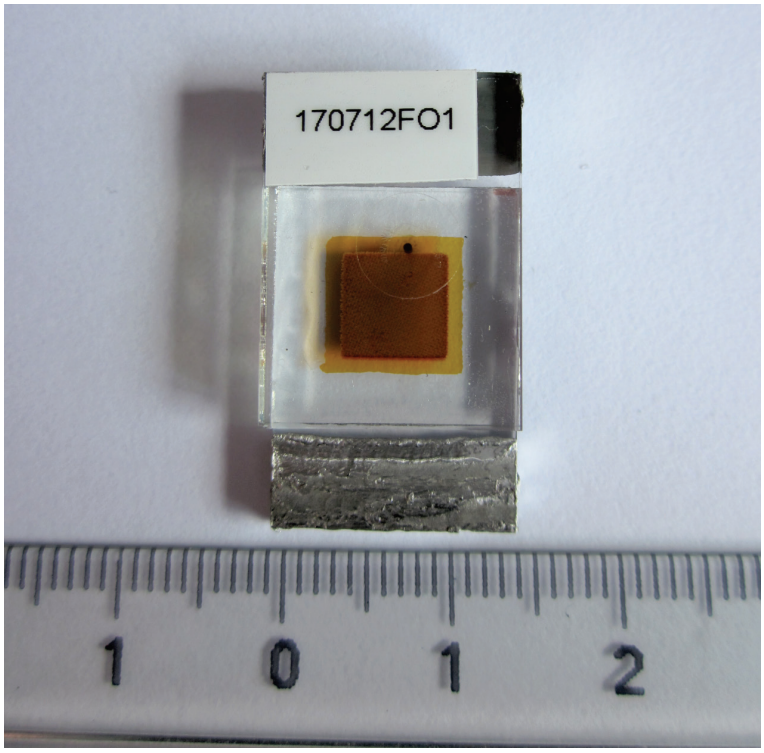


Figure 43 – Typical experimental cell design suitable for the Autolab LED Driver kit

The clamps can be repositioned if necessary by loosening the two screws that hold them in place (see Figure 44).

Note

If the cell does not fit between the two clamps, an external holder can be used to place the cell close to the photodiode. Metrohm Autolab cannot anticipate all the possible cell configurations and it is left to the user to find a suitable solution, if necessary.

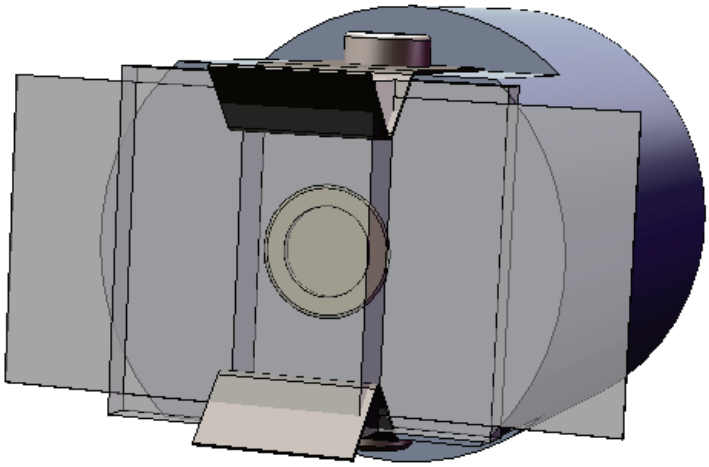


Figure 44 – The cell can be mounted onto the photodiode holder

8 – Experiment description

This section provides a description of different experiments that can be carried out with the LED Driver kit, using the information provided in the previous sections.

8.1 – Cell connections

Photovoltaic devices are usually characterized in the so-called two electrode mode. In this mode, the Autolab PGSTAT is connected to both the anode and the cathode using the CE/RE and WE/S, respectively (see Figure 45).

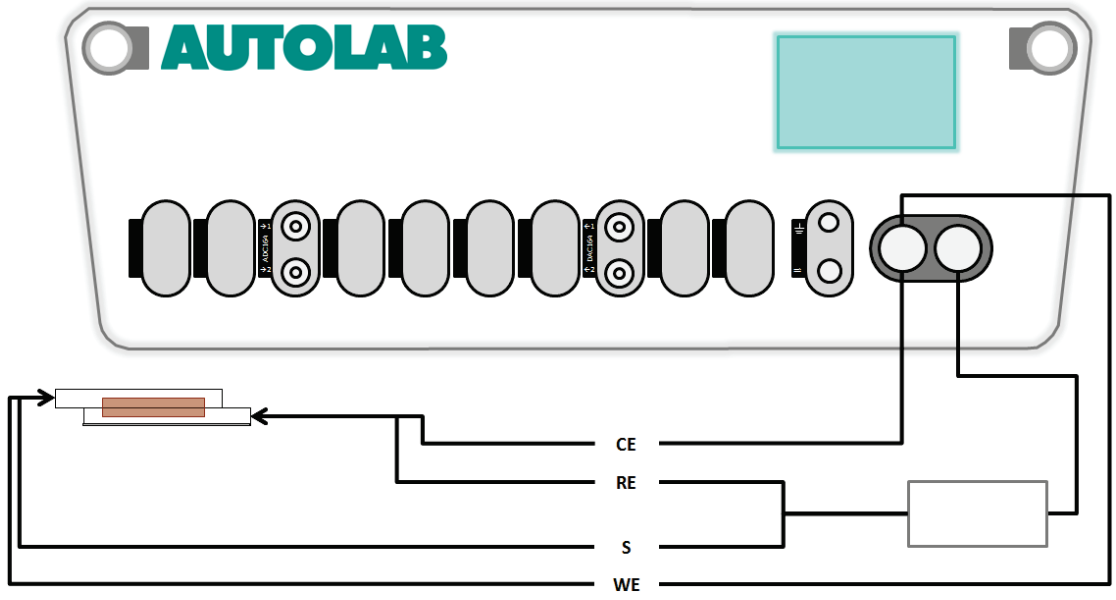


Figure 45 – Overview of the connections to the cell

In this configuration, the potential difference across the cell is measured between the RE and the S, using the differential amplifier electrometer of the Autolab PGSTAT. The current is measured between the CE and the WE.

Note

By convention, the potential of the cell under operating conditions is always positive and the current, under operating conditions is always negative.

8.2 – DC measurements at constant illumination

DC measurements at constant illumination are the simplest measurements possible with the PGSTAT in combination with the LED Driver. During these experiments, the light source is set to a user defined driving current to provide constant illumination on the cell, while the PGSTAT measures the i/V curve of the cell. The i/V curve can be recorded either potentiostatically or galvanostatically.

Note

The Power cannot be measured directly. It can be calculated by multiplying the potential, V, by the current, i.

The following DC measurements are possible:

- Measurement of the i/V curve of the cell
- Charge extraction measurements

8.2.1 – i/V and power curves at constant illumination

Characterization of solar cells usually requires the determination of i/V curves. As the potential of the cell is scanned from 0 V (short circuit conditions) to the open circuit potential, the current changes from the maximum value (short-circuit current, i_{SC}) to OCP (0 A). A typical example is shown in Figure 46.

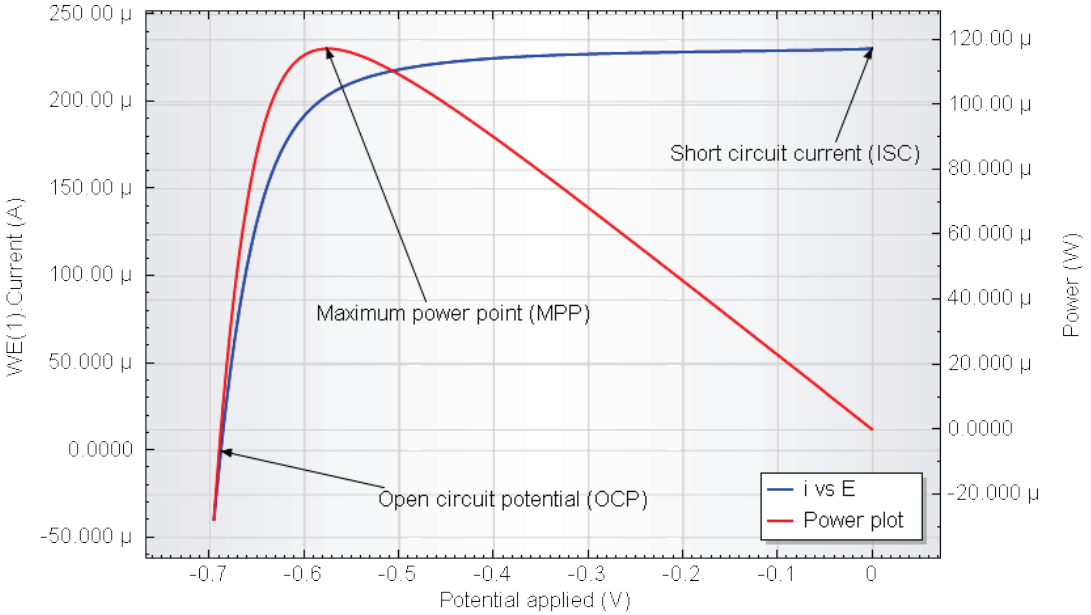


Figure 46 – i/V curve (blue) and power curve (red) obtained with the PGSTAT in combination with a 590 nm LED. The light intensity is 1.655 mW/cm², the cell is a Dye Sensitized Solar Cell

The i/V curves and power curves can be recorded at different light intensities, by varying the driving current. If the conversion of driving current to light intensity in W/cm² is known, then the light intensity to which the cell is exposed can be controlled directly (see Section 6).

From the short circuit current (i_{SC}), open circuit potential (V_{OCP}) and the maximum power point (P_{MAX}), the fill factor (FF) of the cell can be calculated.

$$FF(\%) = \left(\frac{i_{MAX} \cdot V_{MAX}}{i_{SC} \cdot V_{OCP}}\right) \cdot 100 = \left(\frac{P_{MAX}}{i_{SC} \cdot V_{OCP}}\right) \cdot 100$$

$$FF(\%) = \left(\frac{82.558\ \mu W}{186.58\ \mu A \cdot 0.656\ V}\right) \cdot 100 = 61.04\ \%$$

From the light intensity (P_{IN}), the wavelength (λ) and the short-circuit current density (j_{SC}) the incident photon-to-current conversion efficiency (ICPE) can be calculated.

$$IPCE = 1239\left(\frac{j_{SC}}{P_{IN} \cdot \lambda}\right) \cdot 100$$

$$IPCE = 1239\left(\frac{0.325\ mA/cm^2}{1.655\ \frac{mW}{cm^2} \cdot 590\ nm}\right) \cdot 100 = 41.2\ \%$$

8.2.1.1 – Software implementation

DC measurements with the PGSTAT in combination with the LED Driver can be performed using a NOVA procedure. The light intensity can be controlled using the *Control external device (DAC)* command, as explained in Section 5.1.1.

This command can be combined in a measurement with a *LSV staircase* or *LSV staircase galvanostatic* command, depending on the experimental conditions.

Under potentiostatic condition, it is common practice to start the scan a 0 V (short-circuit conditions) and stop the scan when the current becomes zero (open circuit conditions). An example of a procedure for this type of measurement is shown in Figure 47.

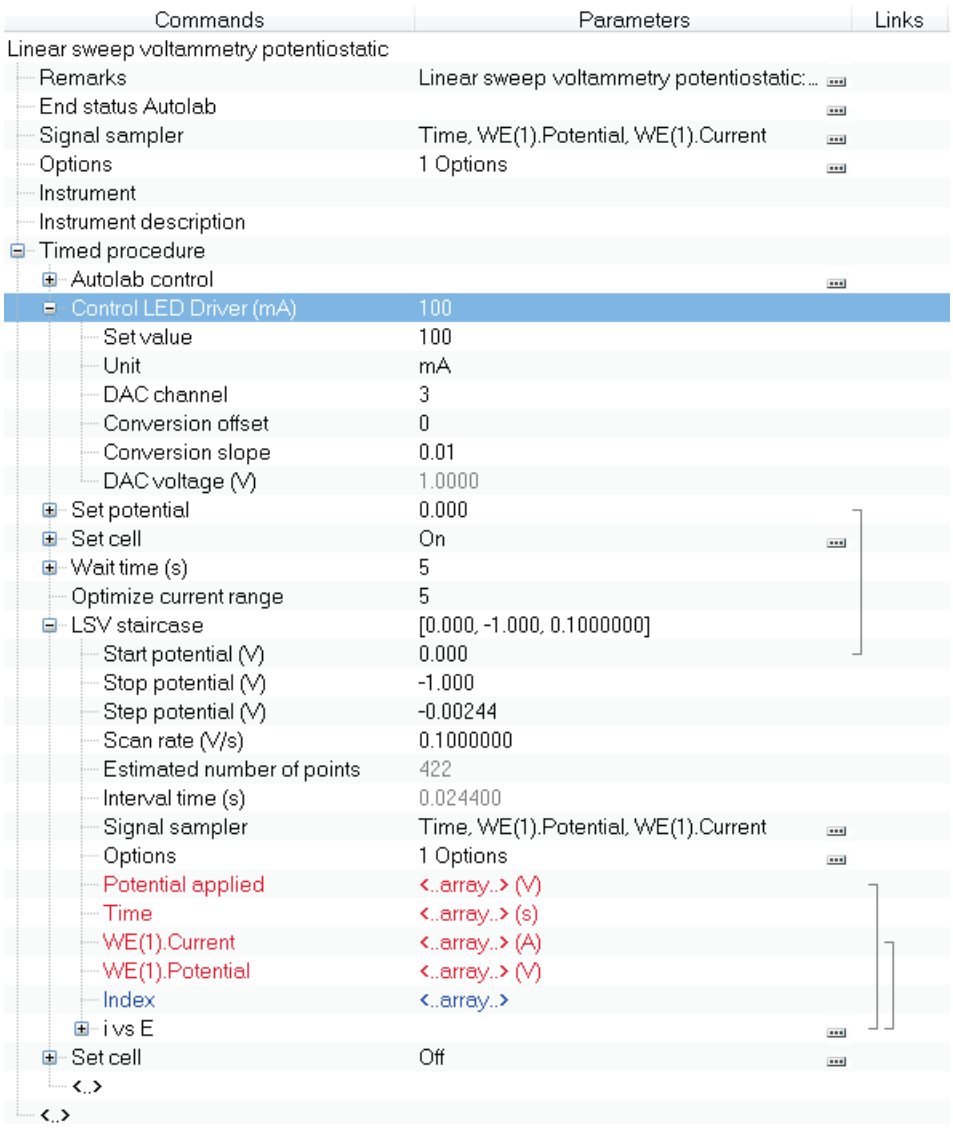


Figure 47 – An example of a procedure used to measure the i/V curve of a cell

Note

A cutoff condition can be used to detect the potential at which the current changes polarity (see Figure 47).

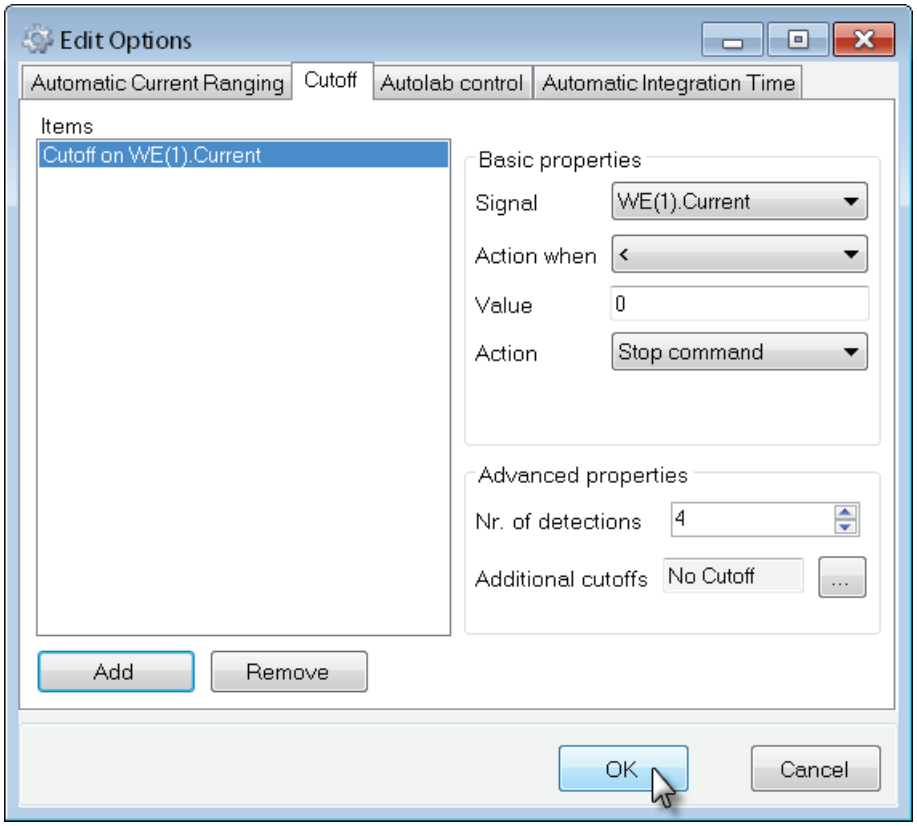


Figure 48 – A cutoff condition can be used to detect the point where the current changes polarity

8.2.1.2 – Possible refinements

The sequence shown in Figure 47 is a very simple sequence which offers limited possibilities. It is possible to combine this sequence with other NOVA commands in order to build a complete measurement sequence. Since the description of such a sequence is left to the requirements of the users, it falls outside of the scope of this document. A few tips are provided below:

- A *Repeat for each value* command, with the set current values defined in the values sequence of the repeat command can be used in combination with the *Control external device (DAC)* command (renamed to *Control LED Driver (mA)*). This will repeat the whole measurement sequence for each pre-defined value (see Figure 49).

- The *Calculate signal* command can be added to the sequence in order to automatically calculate the Power signal, using the values of the potential and the current.

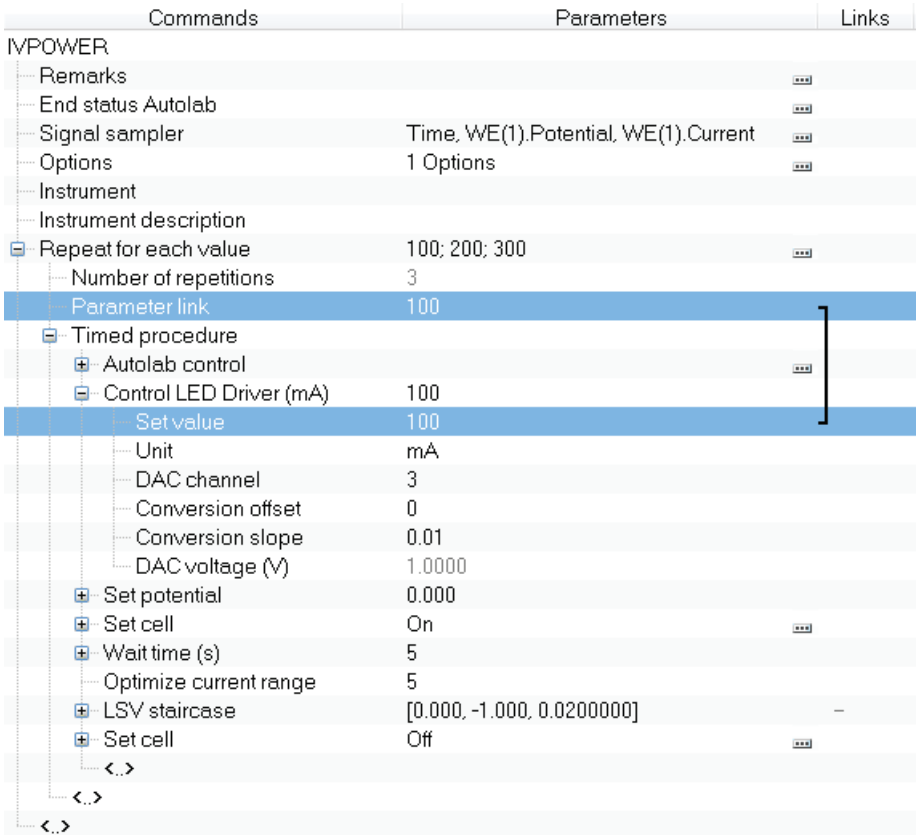


Figure 49 – Using the *Repeat for each value* command in combination with the *Control external device (DAC)* command

8.3 – AC measurements at constant illumination

The LED Driver can be used in combination with the PGSTAT/FRA to obtain the electrochemical impedance spectrum of the device under test (DUT) under constant illumination. Electrochemical impedance measurements can be performed while illuminating the cell, potentiostatically or galvanostatically. Typically, these measurements are performed at open circuit or at short-circuit.

The measurement strategy is the same as for a DC measurement at constant illumination. The light intensity is set to a fixed value using the *Control external device (DAC)* command.

Warning

When performing AC measurements at constant illumination, the of the LED Driver must be shorted using the supplied 50 Ohm terminator plug as explained in Section 4.3.1.

8.3.1 – EIS measurements at constant illumination

The standard Autolab procedure FRA impedance potentiostatic and FRA impedance galvanostatic procedures can be used to perform EIS measurements at constant illumination. The *Control external device (DAC)* command can be added to the preconditioning stage in either one of the procedures. Figure 50 shows a possible procedure that can be used to perform EIS measurements on the DUT.

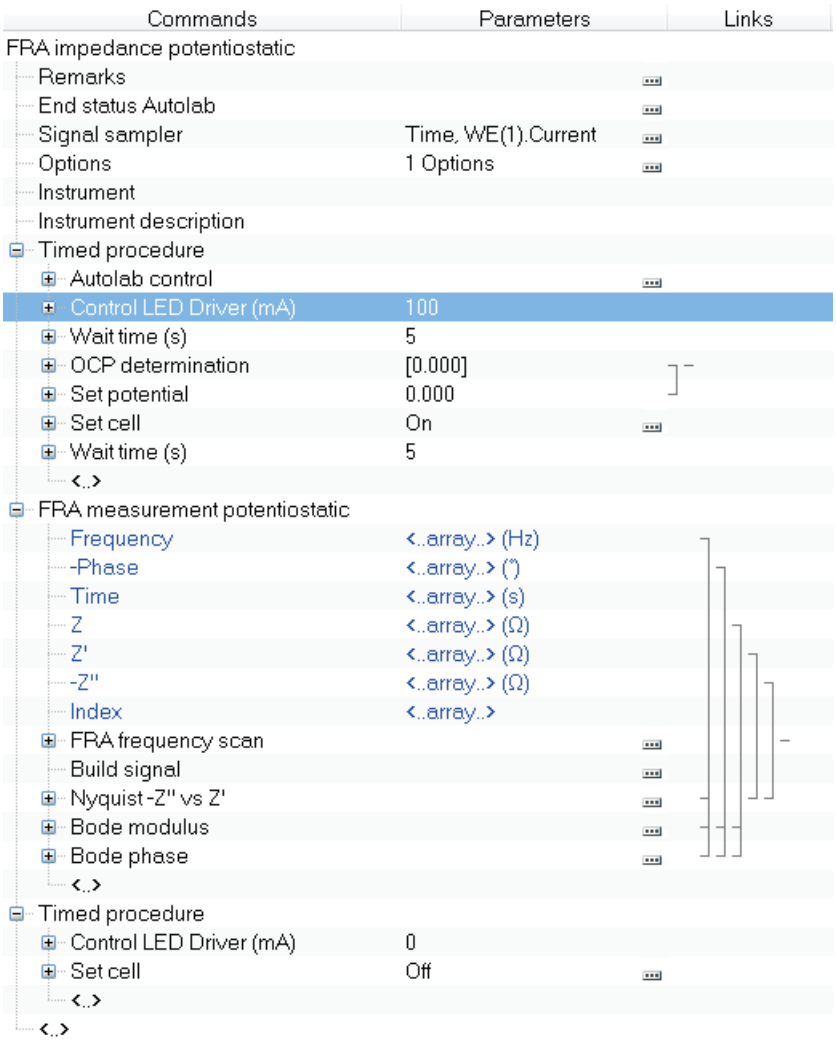


Figure 50 – The FRA impedance potentiostatic procedure modified using the *Control external device (DAC)* command

Note

The *Control external device (DAC)* command is renamed to Control LED Driver (mA) in this example (see Section 5.1.1).

Typical electrochemical impedance spectroscopy measured at different light intensities are illustrated in Figure 51. As the illumination level increases, the Nyquist plot indicates a lower total resistance.

The data shown in Figure 51 has been recorded at 590 nm, at open circuit potential, using an amplitude of 25 mV.

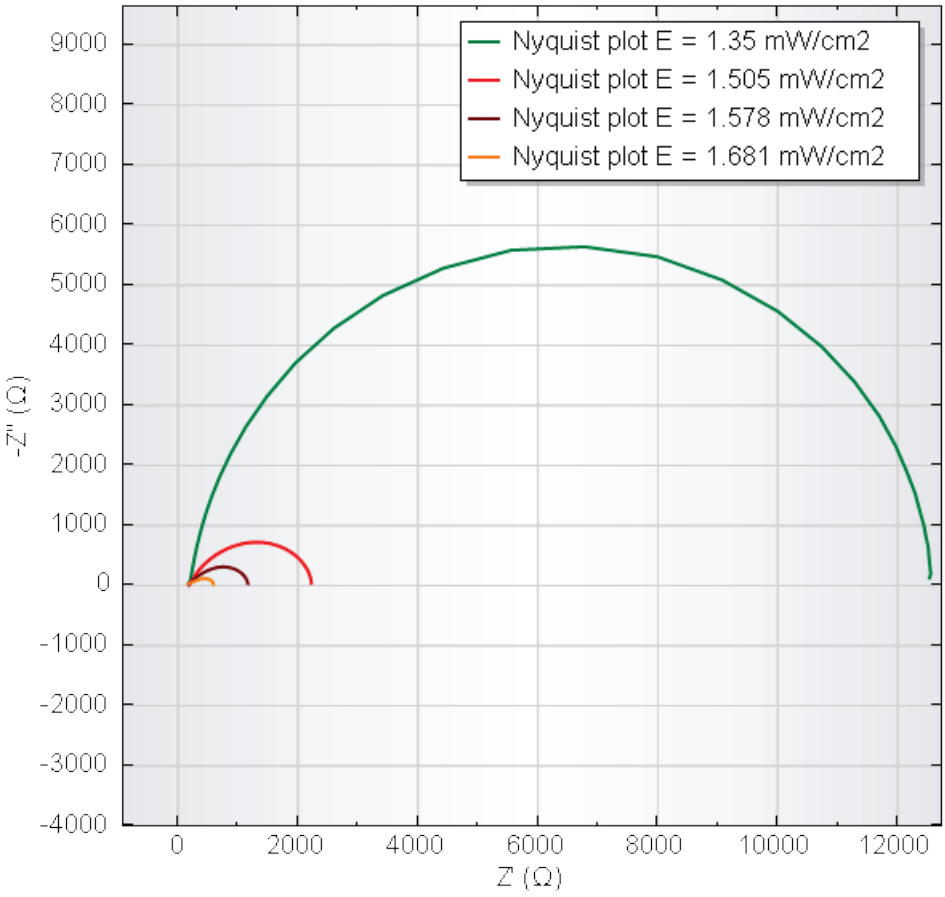


Figure 51 – Typical Nyquist plots recorded at different light intensities

8.4 – AC measurements at modulated illumination

While it is possible to modulate the current or the potential in a classic electrochemical impedance spectroscopy measurement, as explained in Section 8.3.1, it is also possible to modulate the light intensity directly. Two measurement possibilities exist:

- Intensity-modulated photovoltage spectroscopy (IMVS)
- Intensity-modulated photocurrent spectroscopy (IMPS)

8.4.1 – Intensity modulated photovoltage spectroscopy (IMVS)

The LED Driver can be used in combination with the PGSTAT/FRA interface to record intensity modulated photovoltage spectroscopy measurements on the device under test (DUT).

During an intensity modulated photovoltage spectroscopy (IMVS) measurement, the DUT is exposed to a constant light intensity, φ_0, modulated by a small

amplitude AC perturbation, $\Delta\varphi$. The DUT settles at a constant voltage, V_0, modulated by a small amplitude AC response, ΔV.

The IMVS impedance is the transfer function, H, between the AC voltage (ΔV) and the AC light modulation ($\Delta\varphi$).

Figure 52 shows a schematic overview of the experimental setup.

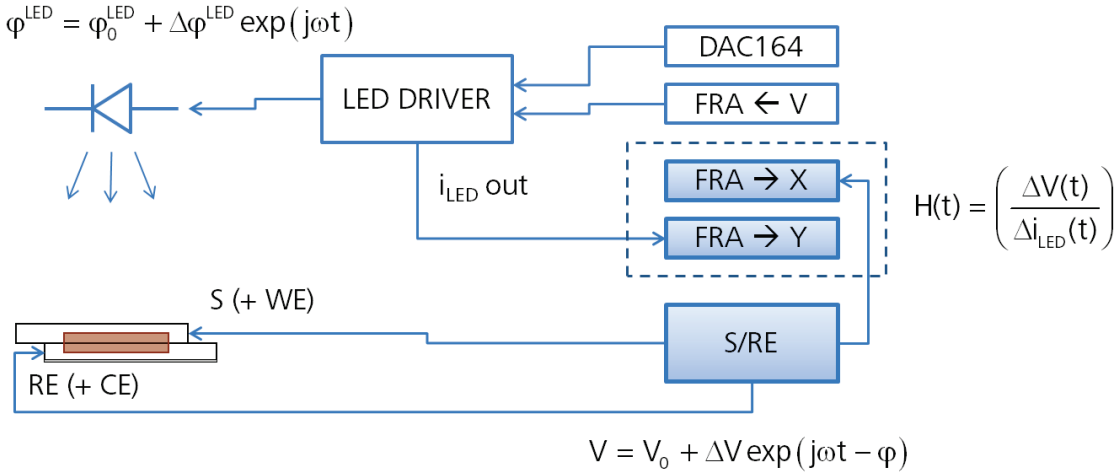


Figure 52 – Overview of the IMVS measurement setup

The fixed light intensity, φ_0 is provided by the DAC voltage using the *Control external device (DAC)* command, as described in the Sections 4.3.1 and 5.1.1. The AC modulation, $\Delta\varphi$, is provided by the FRA ← V connector, using the *FRA measurement external* command, as described in Section 4.3.2 and 5.1.2.

The transfer function, $H(\omega)$, is monitored using the external inputs of the FRA module:

- The E_{out} signal from the PGSTAT is fed into the FRA → X input connector of the FRA module.
- The FRA Y → output of the LED Driver is fed into the FRA → Y input connector of the FRA module.

8.4.1.1 – IMVS measurements

IMVS measurements are usually carried out at open circuit potential (OCP).

Figure 53 shows an example of an IMVS procedure. In the first step of the procedure, the light intensity is set to a fixed DC level using the *Control external device (DAC)* command. The cell is then set open circuit conditions by applying 0 A in Galvanostatic mode.

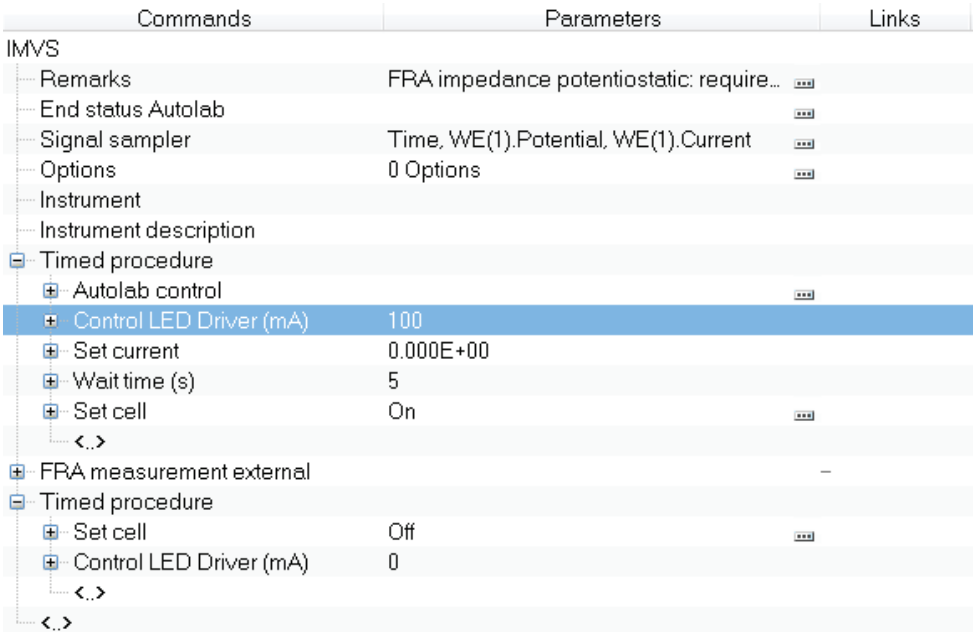


Figure 53 – An example of IMVS procedure

The second stage of the procedure performs the IMVS measurement using the *FRA measurement external* command (see Figure 54).

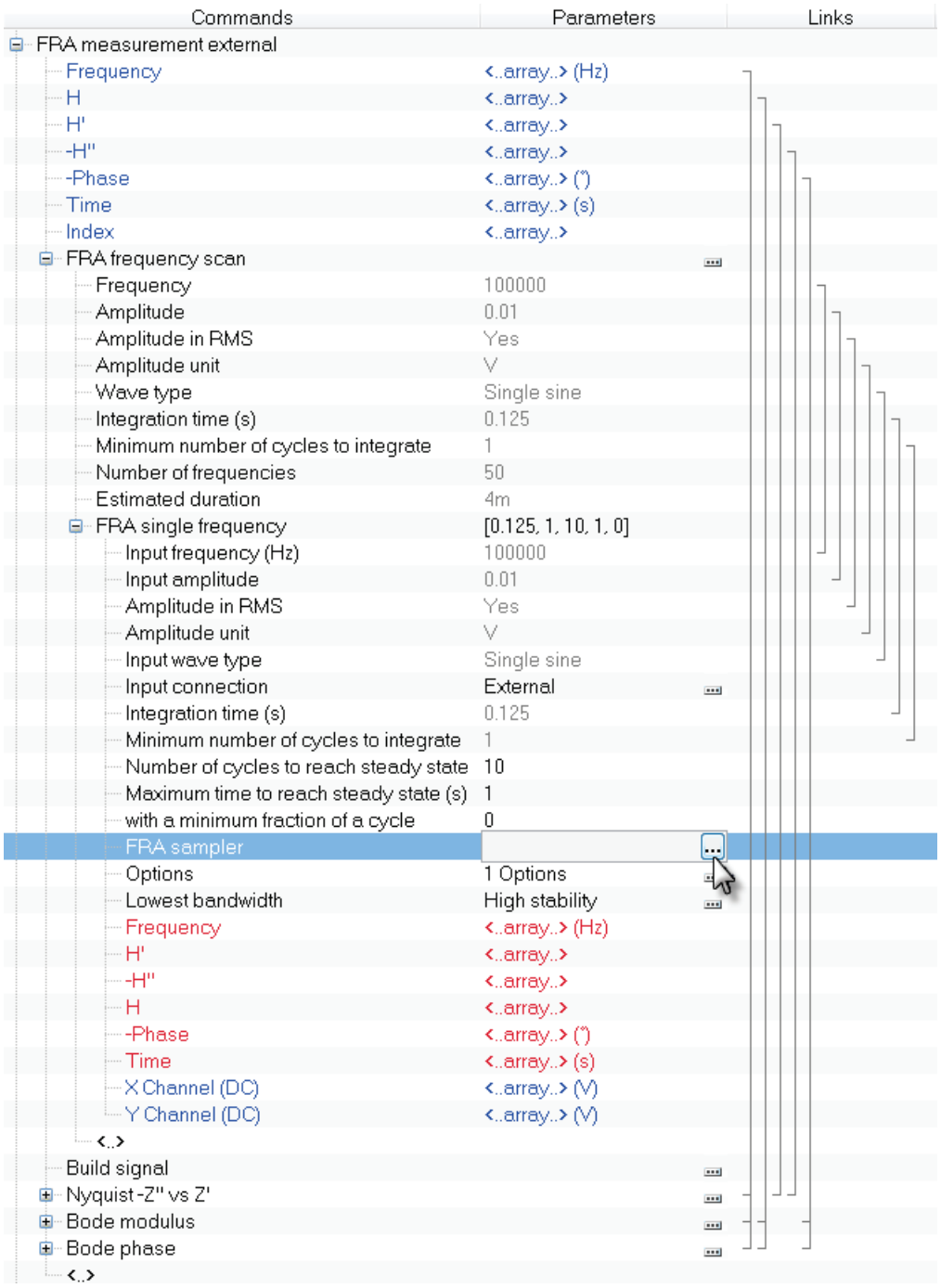


Figure 54 – The *FRA measurement external* command is used during the IMVS frequency scan

Before the measurement can be performed properly, the parameters for the transfer function must be set in the FRA Sampler. Click the ... button located next to the FRA sampler parameter of the FRA signal frequency command (see Figure 54).

The parameters for the transfer function are defined in the Channel X and Channel Y of the FRA sampler window (see Figure 55).

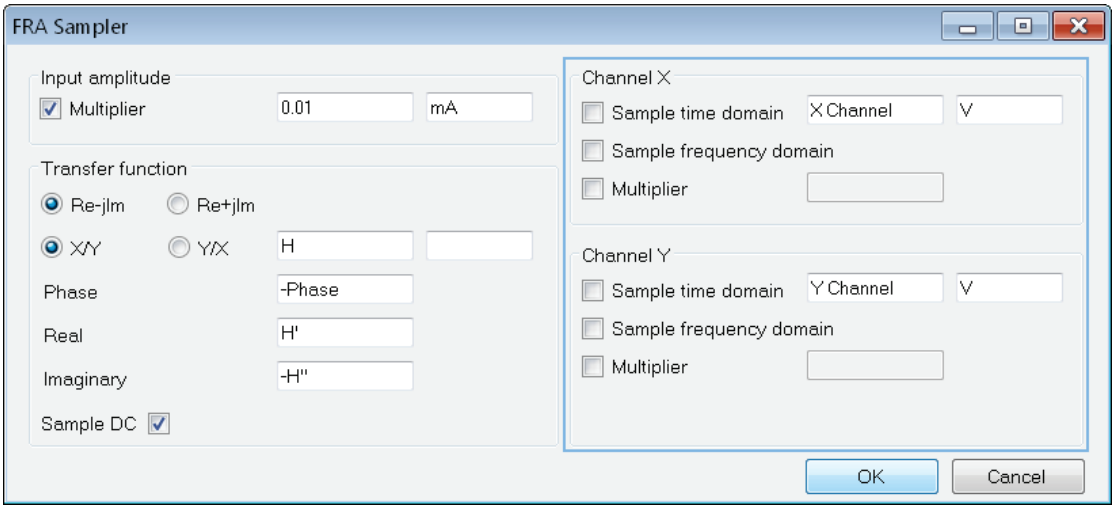


Figure 55 – The transfer function parameters are specified in the FRA sampler (Channel X and Channel Y)

Note

Pin #1, located on DIO port A is used to control the switch. In Figure 54, the parameters for the Input amplitude have already been set according to the instructions indicated in Section 5.1.2.

For IMVS measurements, the following settings are required (see Figure 56):

- **Channel X:** this input is used to measure the AC cell potential during the frequency scan. This input corresponds to the E_{out} coming from the Autolab, which corresponds to the inverted cell potential ($-E_{DUT}$). This input is therefore specified in V and requires a multiplier of (-1).
- **Channel Y:** this input is used to the measure the AC LED Driver current during the frequency scan. The FRA Y → output of the LED Driver is connected to this input. The values from this connection are expressed in V (corresponding to the converted current). The conversion factor is 1 V/A. This signal is therefore specified in A and requires a multiplier of 1.

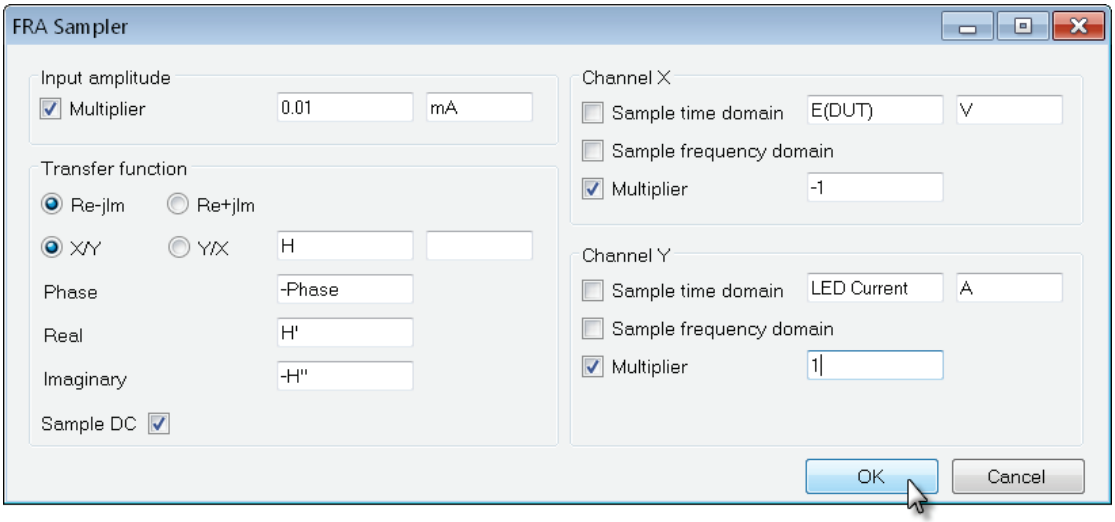


Figure 56 – Setting the parameters for the FRA sampler

Note

Using the FRA sampler window, it is possible to specify if the time domain information, corresponding to the raw sinewaves recorded by the FRA module, have to be sampled during the measurement[1]. It is recommended to check both checkboxes for IMVS measurements, in order to verify the quality of the data during the experiments (see Figure 56).

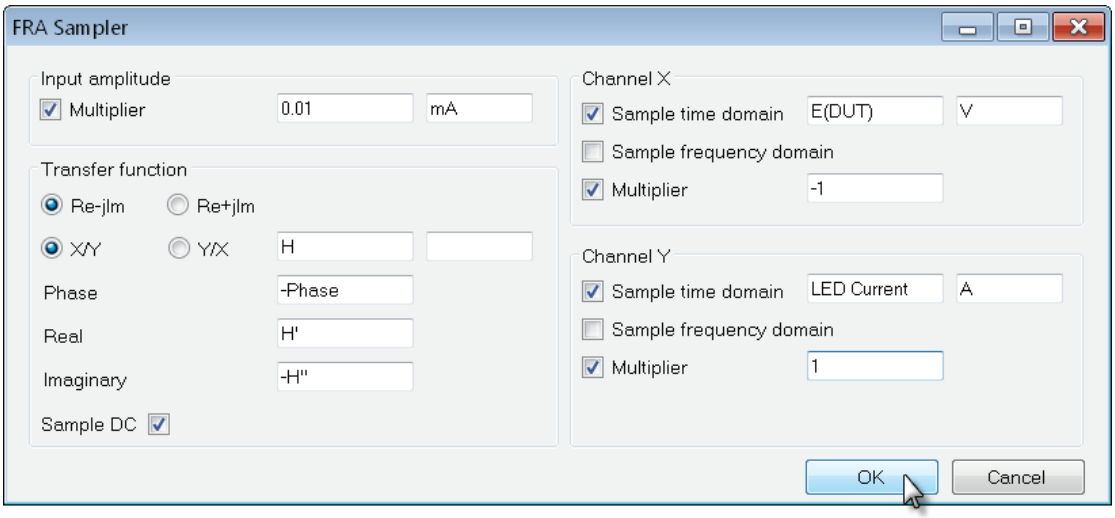


Figure 57 – Sampling the time domain data for Channel X and Channel Y

Close the FRA sampler with the OK button.

The frequency scan can now be defined in the procedure editor by clicking the ... button next to the FRA frequency scan command (see Figure 58).

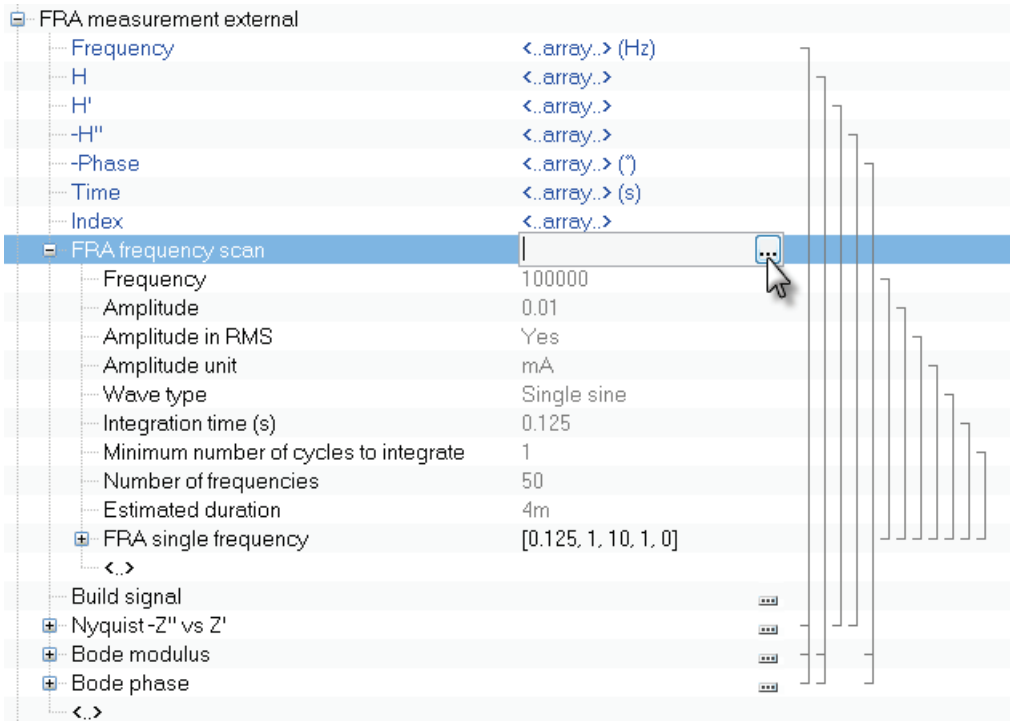


Figure 58 – Opening the FRA frequency scan editor

The FRA frequency scan window will be displayed. The highest frequency, lowest frequency, number of frequencies and frequency distribution can be defined in this editor (see Figure 59). The amplitude can also be defined in mA (or in A, depending on the settings used in the FRA sampler).

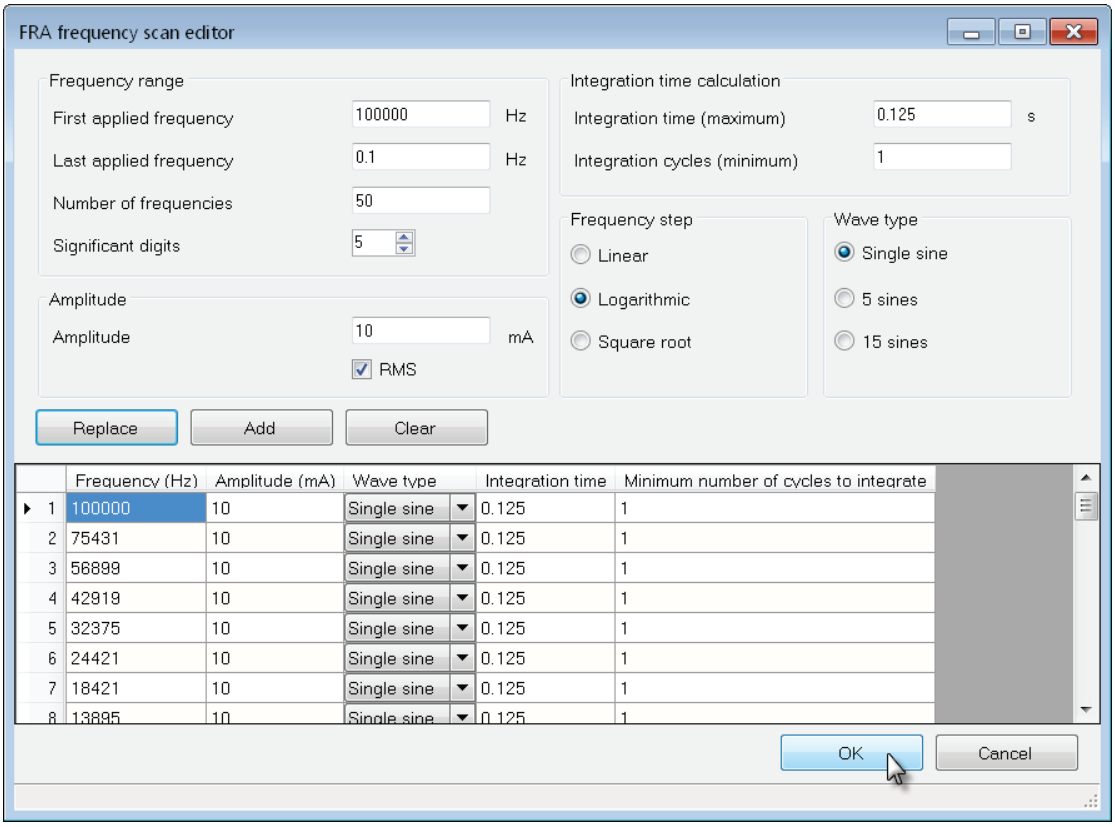


Figure 59 – The FRA frequency scan editor window

Once the frequency range is defined, the measurement can be performed. Figure 60 shows a typical IMVS measurement on a DSC. The measurement is performed at 590 nm, at a constant light intensity of 1.7 mW/cm^2. The AC amplitude is 10 % of the DC light intensity.

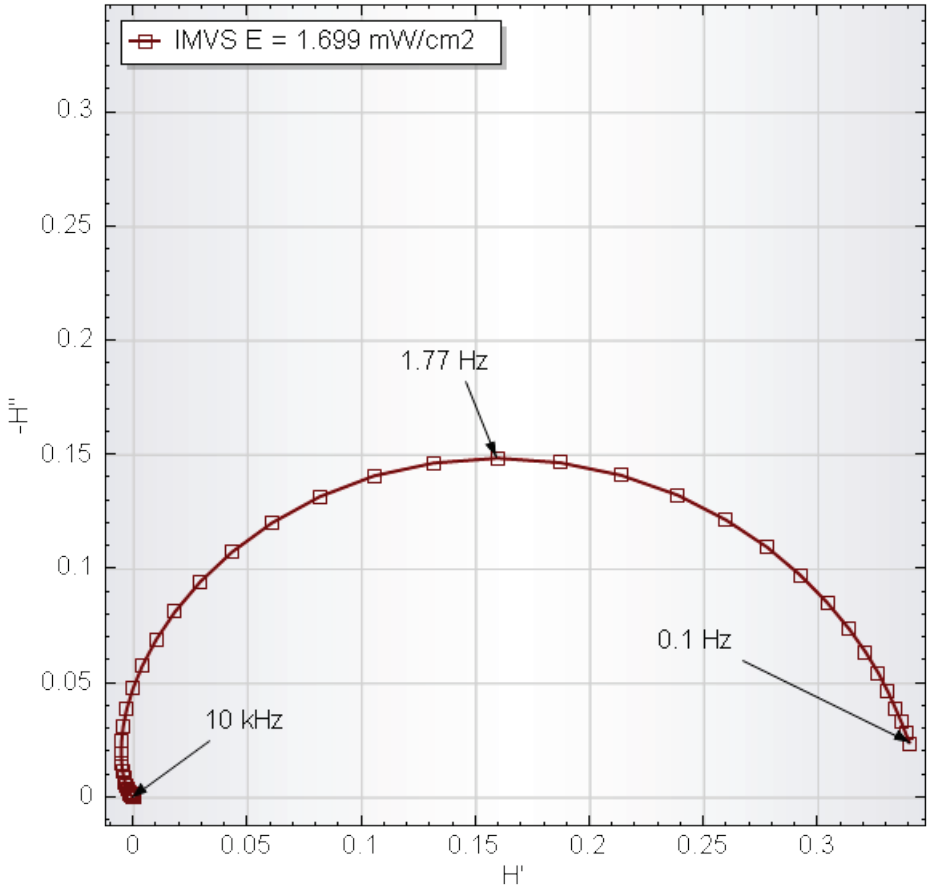


Figure 60 – A typical IMVS measurement on a dye-sensitized solar cell

8.4.2 – Intensity modulated photocurrent spectroscopy (IMPS)

The LED Driver can be used in combination with the PGSTAT/FRA to record intensity modulated photocurrent spectroscopy measurements on the device under test (DUT).

During an intensity modulated current spectroscopy (IMPS) measurement, the DUT is exposed to a constant light intensity, φ_0, modulated by a small amplitude AC perturbation, $\Delta\varphi$. The DUT settles at a constant current, i_0, modulated by a small amplitude AC response, Δi.

The IMPS impedance is the transfer function, H, between the AC current (Δi) and the AC light modulation ($\Delta\varphi$).

Figure 61 shows a schematic overview of the experimental setup.

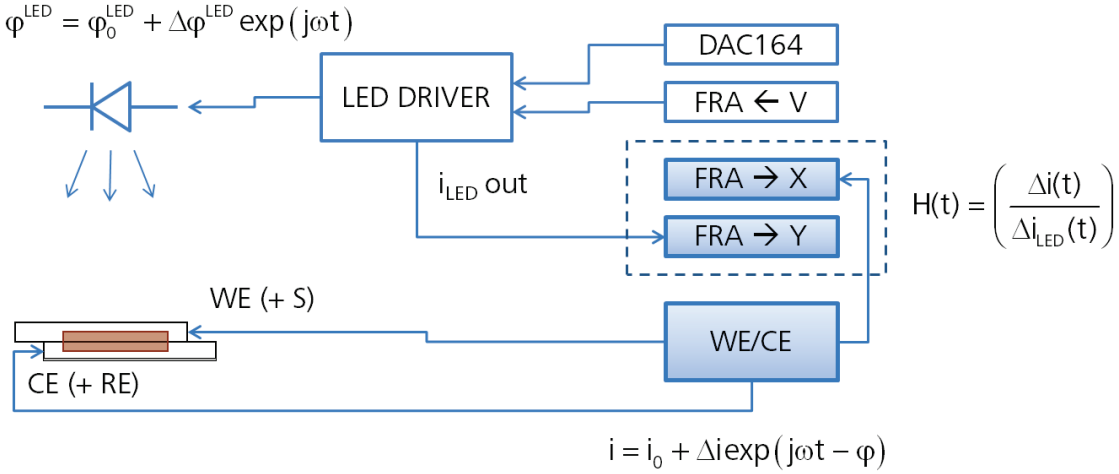


Figure 61 – Overview of the IMPS measurement setup

The fixed light intensity, φ_0 is provided by the DAC voltage using the *Control external device (DAC)* command, as described in the Sections 4.3.1 and 5.1.1. The AC modulation, $\Delta\varphi$, is provided by the FRA ← V connector, using the *FRA measurement external* command, as described in Sections 4.3.2 and 5.1.2.

The transfer function, $H(\omega)$, is monitored using the external inputs of the FRA module:

- The i_{out} signal from the PGSTAT is fed into the FRA → X input connector of the FRA module.
- The FRA Y → output of the LED Driver is fed into the FRA → Y input connector of the FRA module.

Warning

The automatic current ranging option **cannot** be used in an IMPS measurement.

8.4.2.1 – IMPS measurements

IMPS measurements are usually carried out at short-circuit conditions.

Figure 62 shows an example of an IMPS procedure. In the first step of the procedure, the light intensity is set to a fixed DC level using the *Control external device (DAC)* command. The potential is set to 0 V (short-circuit conditions).

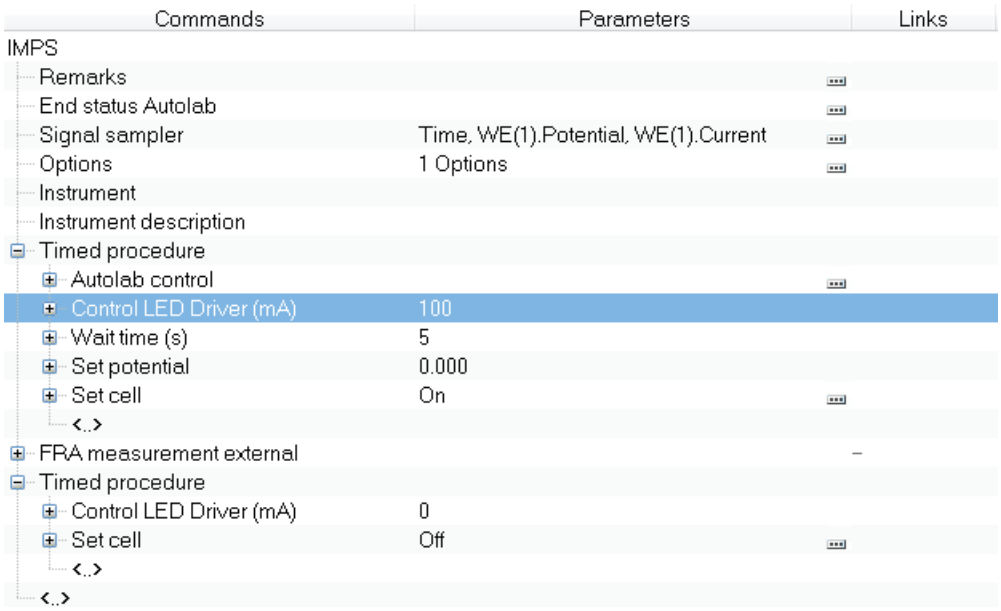


Figure 62 – An example of IMPS procedure

The second stage of the procedure performs the IMPS measurement using the *FRA measurement external* command (see Figure 63).

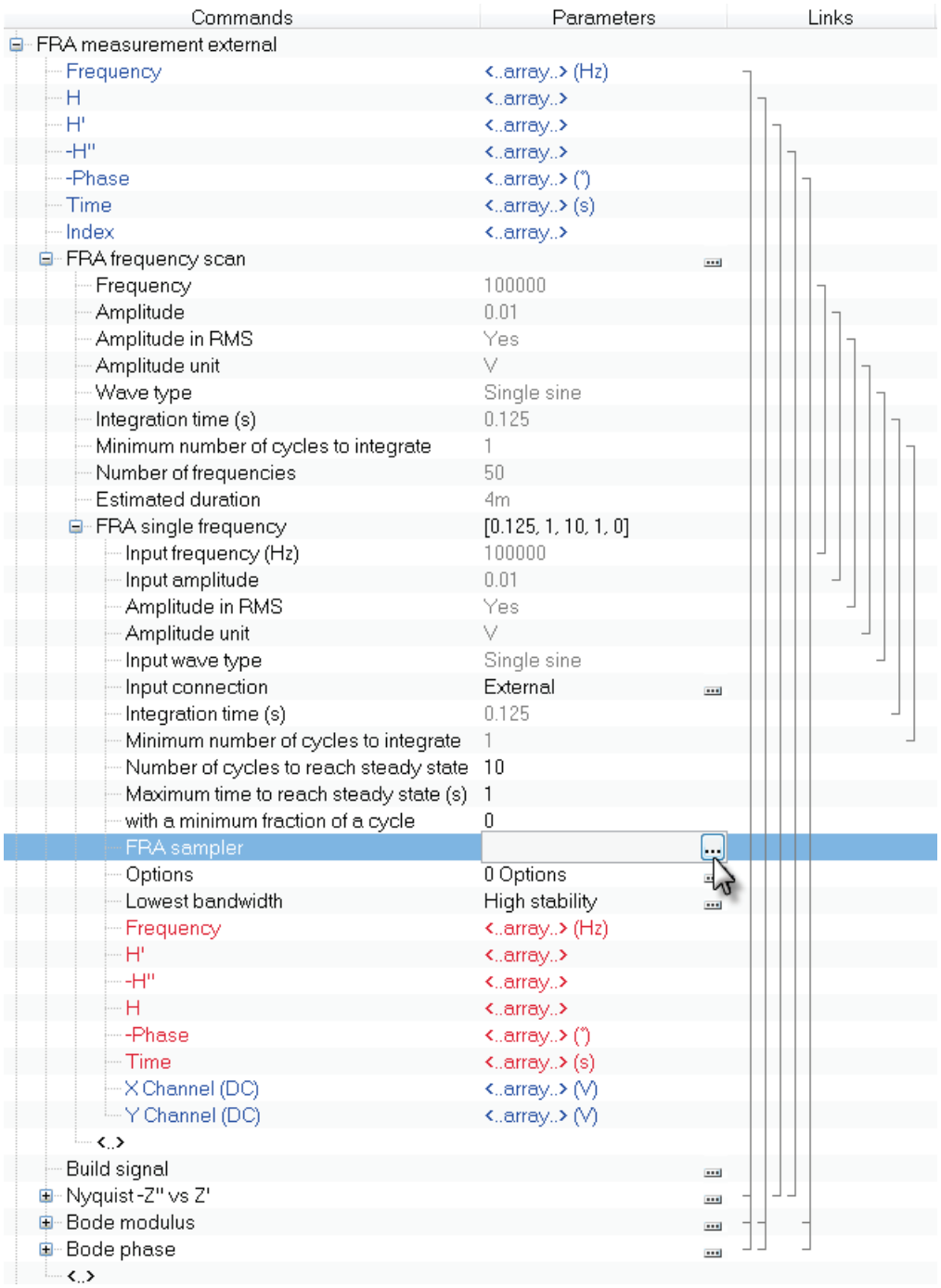


Figure 63 – The *FRA measurement external* command is used during the IMPS frequency scan

Before the measurement can be performed properly, the parameters for the transfer function must be set in the FRA Sampler. Click the ... button located next to the FRA sampler parameter of the FRA signal frequency command (see Figure 63).

The parameters for the transfer function are defined in the Channel X and Channel Y of the FRA sampler window (see Figure 64).

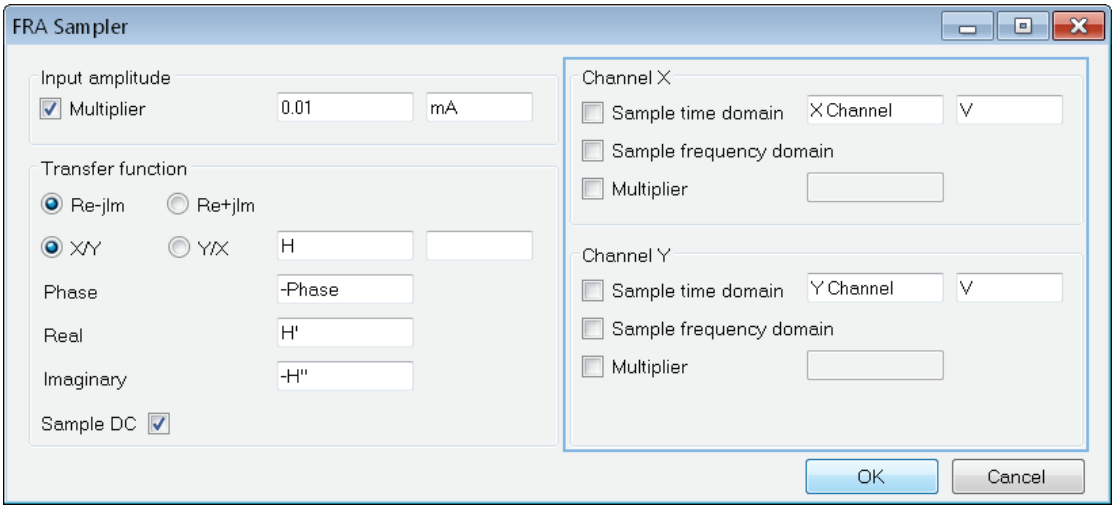


Figure 64 – The transfer function parameters are specified in the FRA sampler (Channel X and Channel Y)

Note

In Figure 63, the parameters for the Input amplitude have already been set according to the instructions indicated in Section 5.1.2.

For IMPS measurements, the following settings are required (see Figure 65):

- **Channel X:** this input is used to measure the AC cell current during the frequency scan. This input corresponds to the i_{out} coming from the Autolab, which corresponds to the converted cell current (which depends on the selected current range[7]). This input is therefore specified in A and requires a multiplier that depends on the current range used in the measurement. The i_{out} of the Autolab is given by the measured current (in A) divided by the current range (in A/V). Table 2 shows the multiplier values depending on the selected current range. Figure 65 shows the settings for a measurement in the 1 mA current range.

[7] Please refer to the NOVA Getting Started manual for more information.

Current range	Conversion factor	Multiplier
1 A	1 A/V	1
100 mA	100 mA/V	0.1
10 mA	10 mA/V	0.01
1 mA	1 mA/V	0.001
100 µA	100 µA/V	0.0001
10 µA	10 µA/V	0.00001
1 µA	1 µA/V	0.000001
100 nA	100 nA/V	0.0000001
10 nA	10 nA/V	0.00000001

Table 2 – Multiplier factors per current range

- **Channel Y:** this input is used to the measure the AC LED Driver current during the frequency scan. The FRA Y → output of the LED Driver is connected to this input. The values from this connection are expressed in V (corresponding to the converted current). The conversion factor is 1 V/A. This signal is therefore specified in A and requires a multiplier of 1.

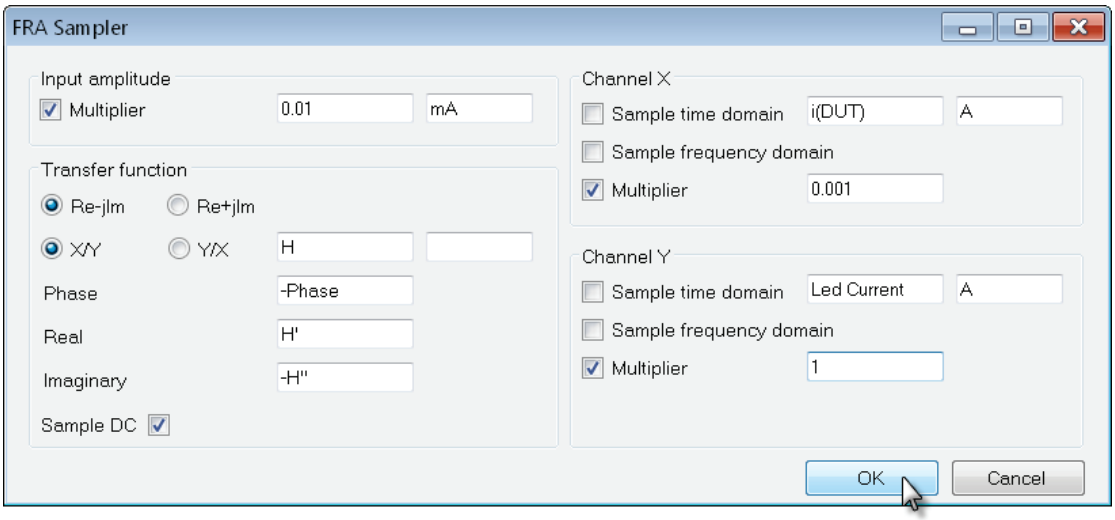


Figure 65 – Setting the parameters for the FRA sampler

Note

Using the FRA sampler window, it is possible to specify if the time domain information, corresponding to the raw sinewaves recorded by the FRA module, have to be sampled during the measurement[1]. It is recommended to check both checkboxes for IMPS measurements, in order to verify the quality of the data during the experiments (see Figure 65).

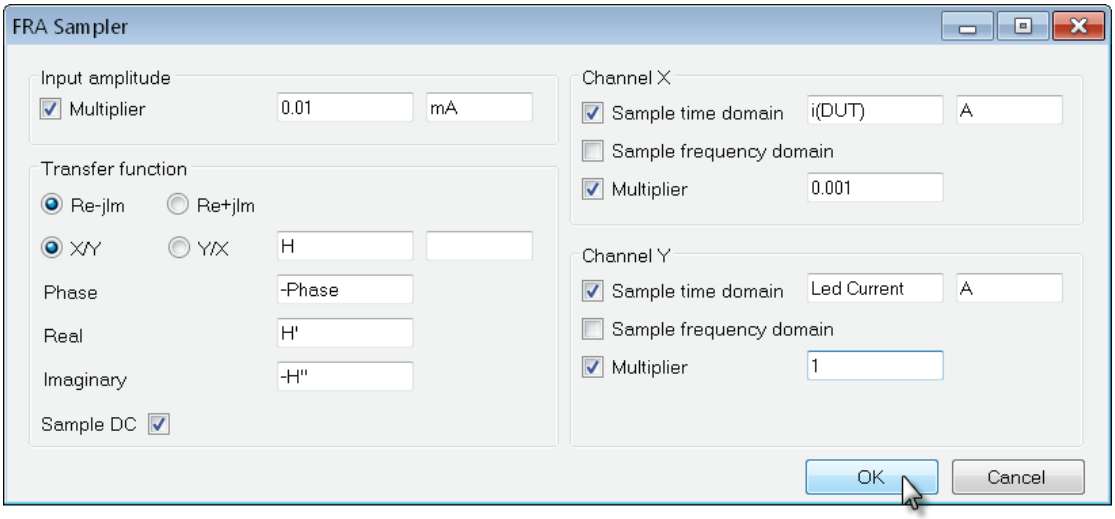


Figure 66 – Sampling the time domain data for Channel X and Channel Y

Close the FRA sampler with the OK button.

The frequency scan can now be defined in the procedure editor by clicking the ... button next to the FRA frequency scan command (see Figure 67).

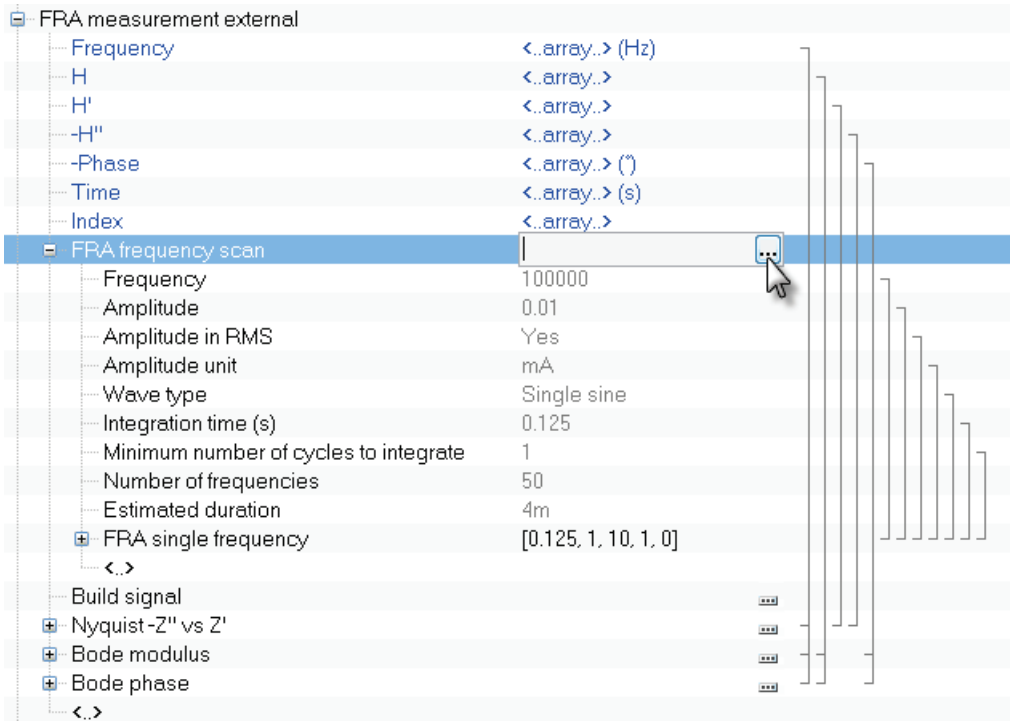


Figure 67 – Opening the FRA frequency scan editor

The FRA frequency scan window will be displayed. The highest frequency, lowest frequency, number of frequencies and frequency distribution can be defined in this editor (see Figure 68). The amplitude can also be defined in mA (or in A, depending on the settings used in the FRA sampler).

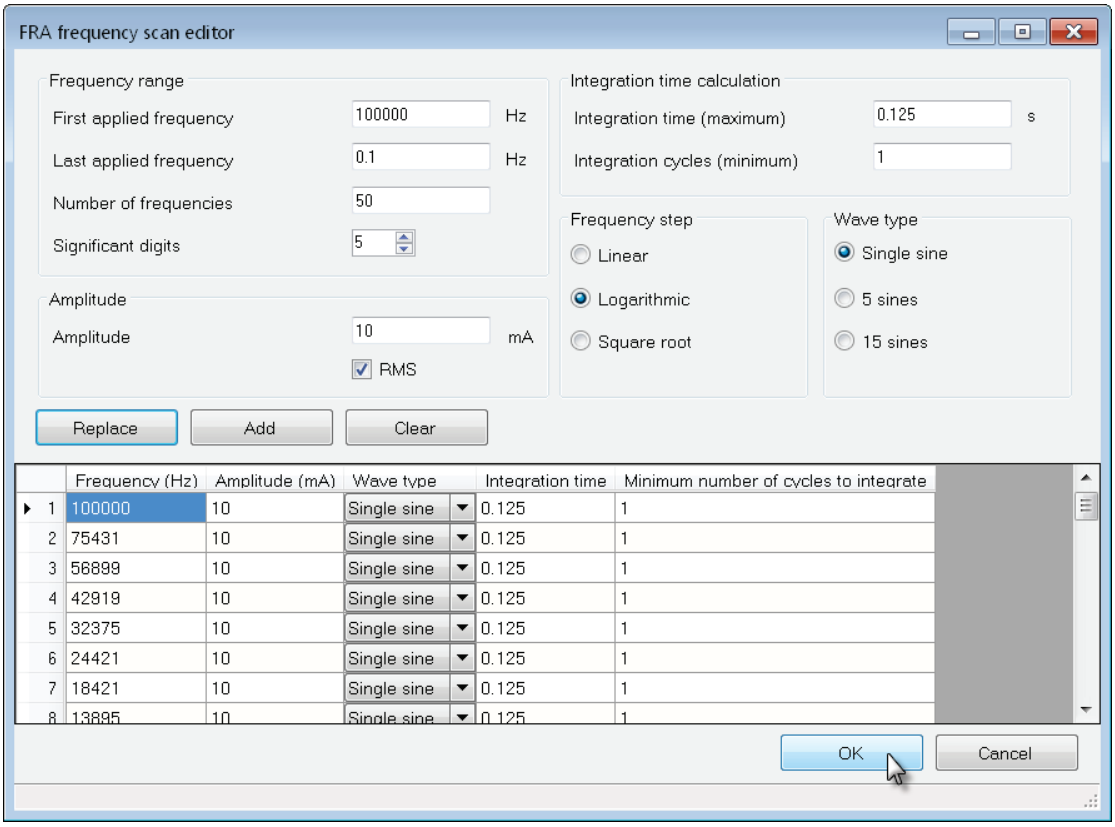


Figure 68 – The FRA frequency scan editor window

Once the frequency range is defined, the measurement can be performed. Figure 69 shows a typical IMPS measurement on a DSC. The measurement is performed at 590 nm, at a constant light intensity of 1.7 mW/cm^2. The AC amplitude is 10 % of the DC light intensity.

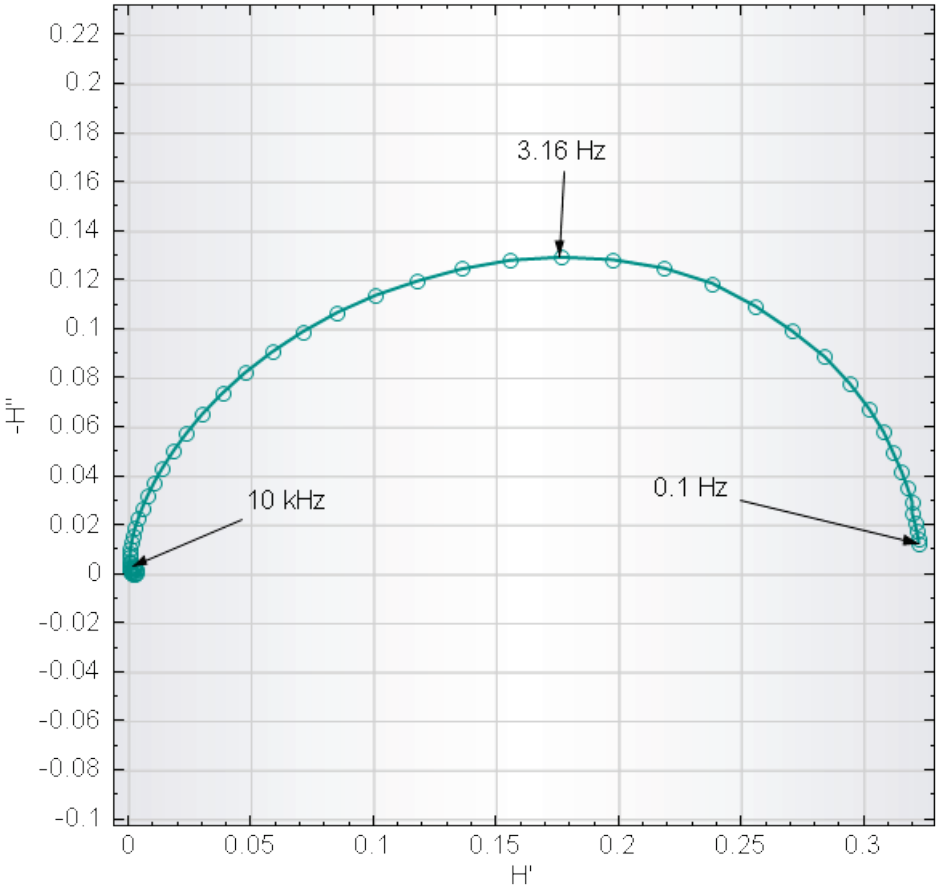


Figure 69 – A typical IMPS measurement on a DSC

8.5 – Safety settings when measurement is aborted

When measurements are manually interrupted, by clicking the Stop button, or when a cutoff condition is met that stops the complete procedure, it may be necessary to completely switch off the light source and the cell.

To define the end conditions for the Autolab LED Driver kit and the cell, the End status Autolab settings can be defined in the procedure editor.

The End status Autolab can be defined by clicking the ... button next to this parameter in the procedure editor (see Figure 70).

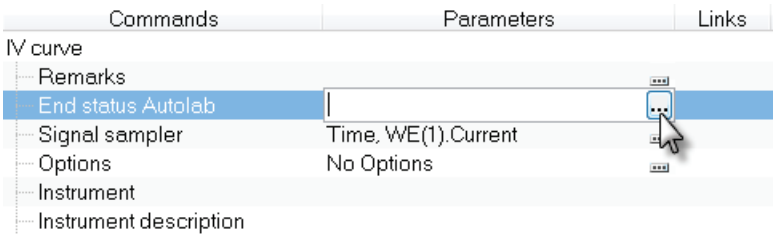


Figure 70 – Editing the End status Autolab

The Autolab control editor will be displayed (see Figure 71). Using the drop-down boxes, the required adjustments can be defined.

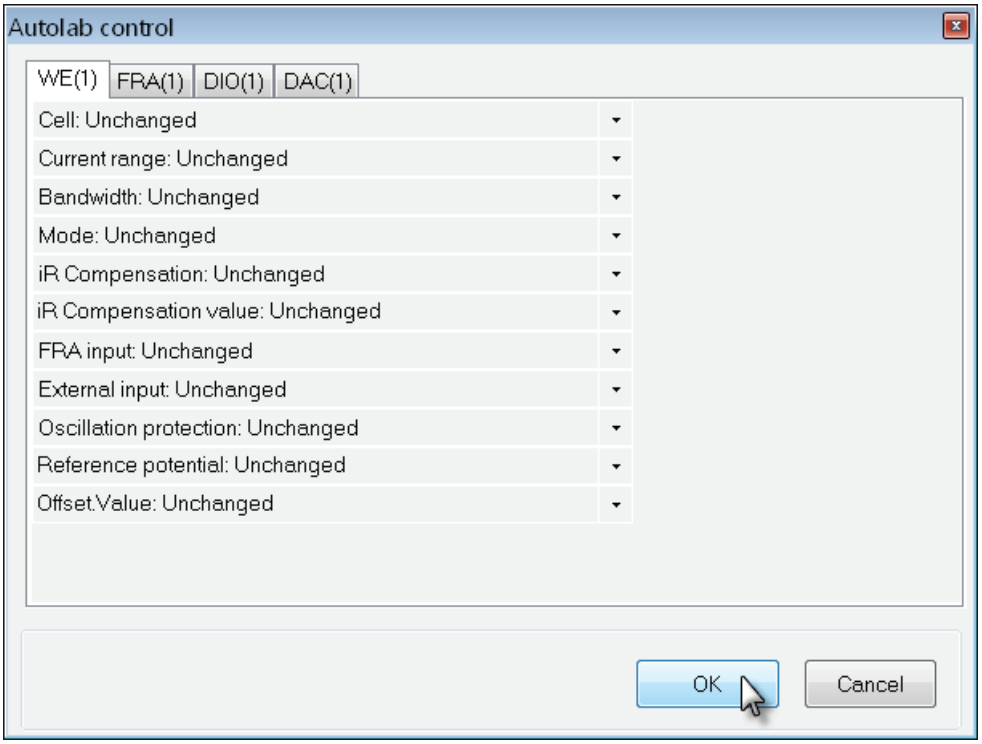


Figure 71 – The End status Autolab is defined using the Autolab control window

The following settings can be relevant for this application:

- **Cell off:** to switch the cell off, set the Cell drop-down list on the WE(1) tab of the Autolab control window to Off (see Figure 72).

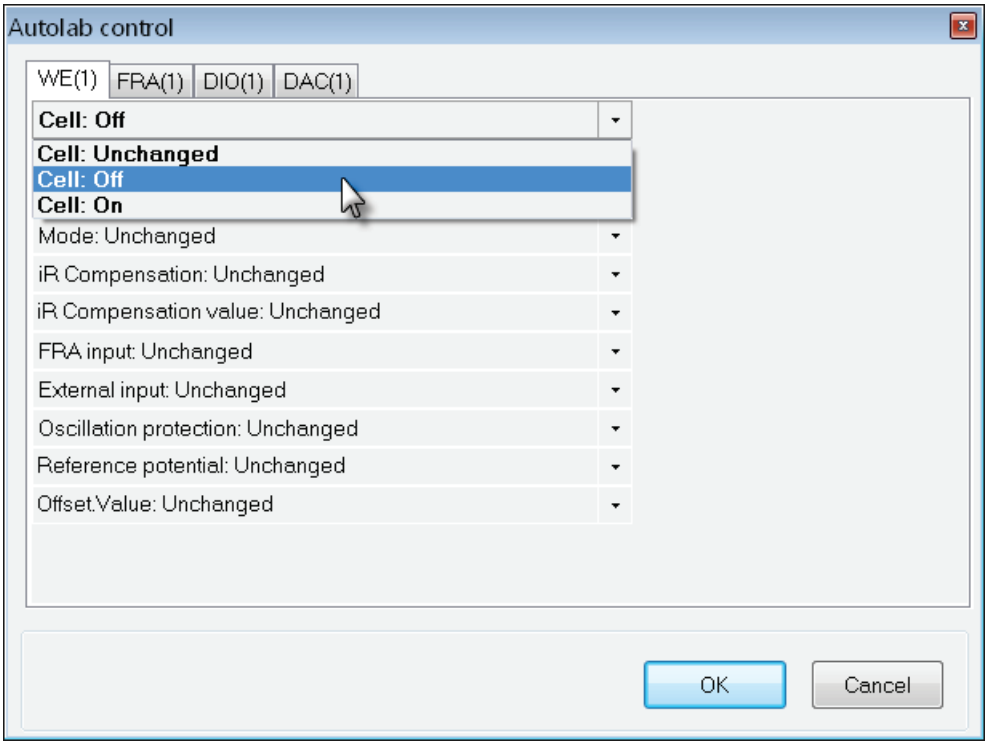


Figure 72 – Switching the cell off

- **Light off:** to switch the light source off, set the DAC voltage property to 0 V on the DAC(1) tab (see Figure 73).

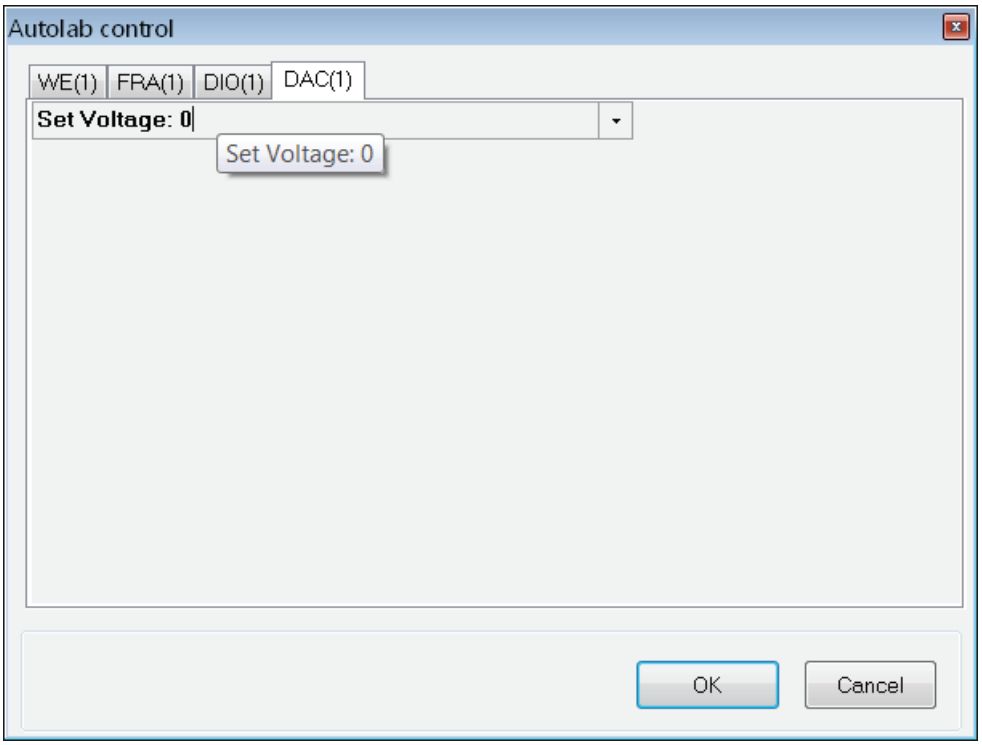


Figure 73 – Setting the DAC voltage to 0 V

- **Modulation off:** to switch off the modulation generated by the FRA module, if applicable, set the DSG property to off using the provided drop-down list on the FRA(1) tab (see Figure 74).

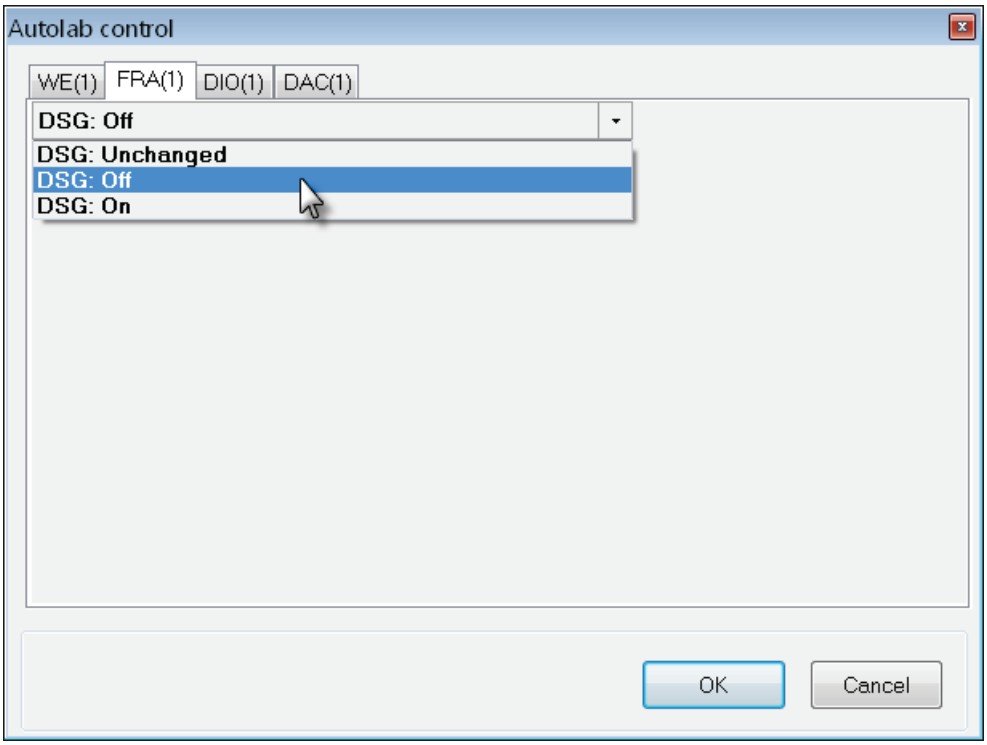


Figure 74 – Switching the output of the FRA module off

9 – Thermal considerations

Although the LED holder has been designed for optimal temperature management, the behaviour of the LEDs located onto the PCB is affected by temperature variations. Since the overall temperature of the LED PCB increases as the driving current increases, the light output can be affected, leading to a non-linear relationship between driving current and light intensity.

Figure 75 and Figure 76 show how the relative light output of the LEDs is affected by the temperature. The light intensity is normalized with respect to the light intensity measured at 25 °C.

Warning

The LED light source can get hot when operated at high driving currents. Always allow the light source to cool down before touching it.

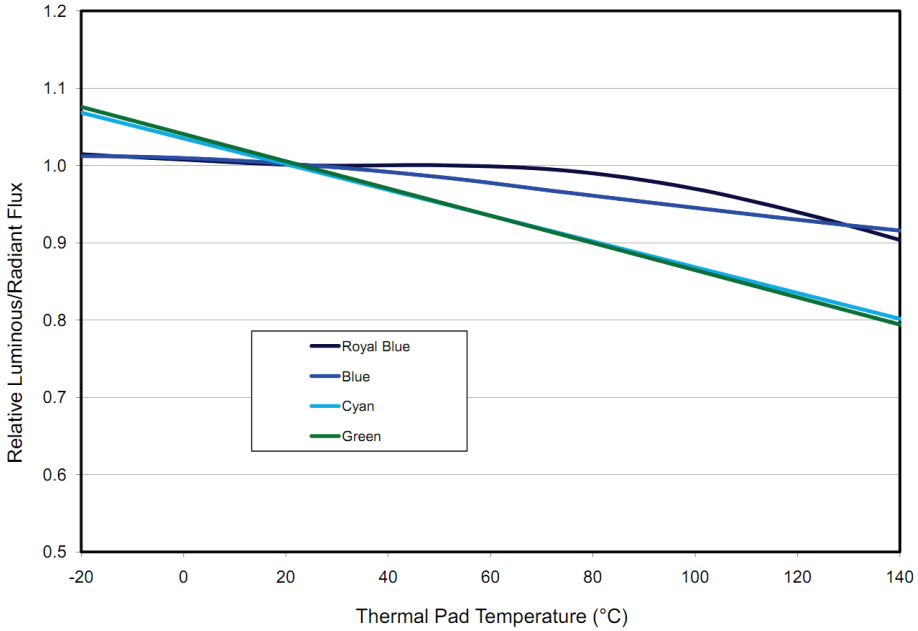


Figure 75 – Relative light output vs thermal pad temperature for green, cyan, blue and royal-blue[8]

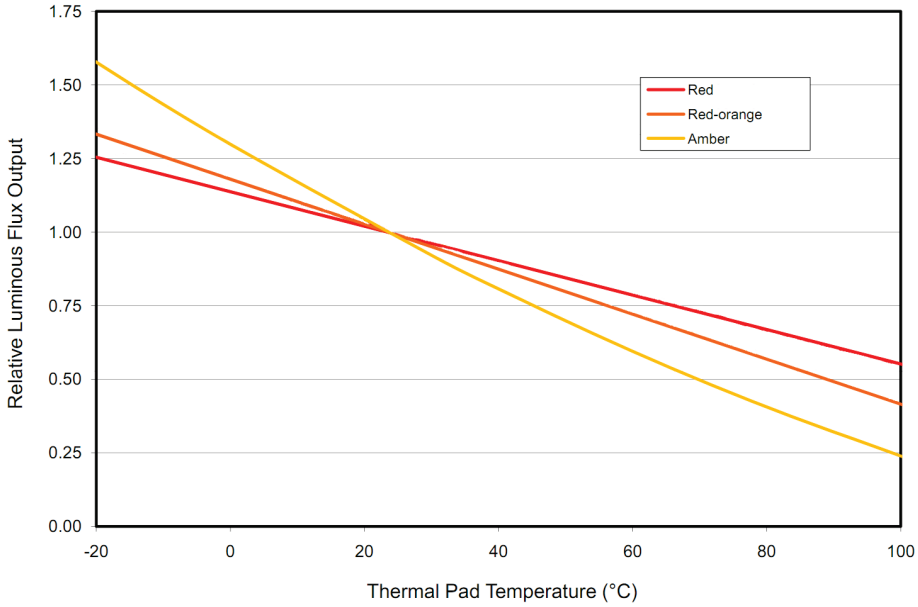


Figure 76 – Relative light output vs thermal pad temperature for red, red-orange and amber[9]

[8] Adapted from LUXEON Rebel, Direct Color Portfolio, High power, colored LEDs, Technical Datasheet DS65.
[9] Adapted from LUXEON Rebel, Direct Color Portfolio, High power, colored LEDs, Technical Datasheet DS65.

Appendix 1 – Modification of the input range of the FRA2 module

By default, the external inputs of the FRA2 modules shipped before July 2009 (revision number 8.0 and lower) can be used to record analog signals in the ± 5 V range. For this application, analog signals in the ± 10 V range are required. In order to be able to record voltages between 5 and 10 V, the FRA2 modules with revision numbers lower than 8.1 need to have the extended range offset DACs activated.

This requires a simple hardware modification. Only qualified personnel can perform this modification. Please contact Metrohm Autolab B.V. (info@metrohm-autolab.com) or your local distributor for more information.

Note

This modification is not applicable for the µAutolabIII/FRA2.

The FRA2 input range is directly specified in the Hardware setup. Start NOVA and open the Hardware setup (Tools – Hardware setup). Locate the FRA2 offset DAC range toggle at the bottom of the Hardware setup window (see Figure 77).

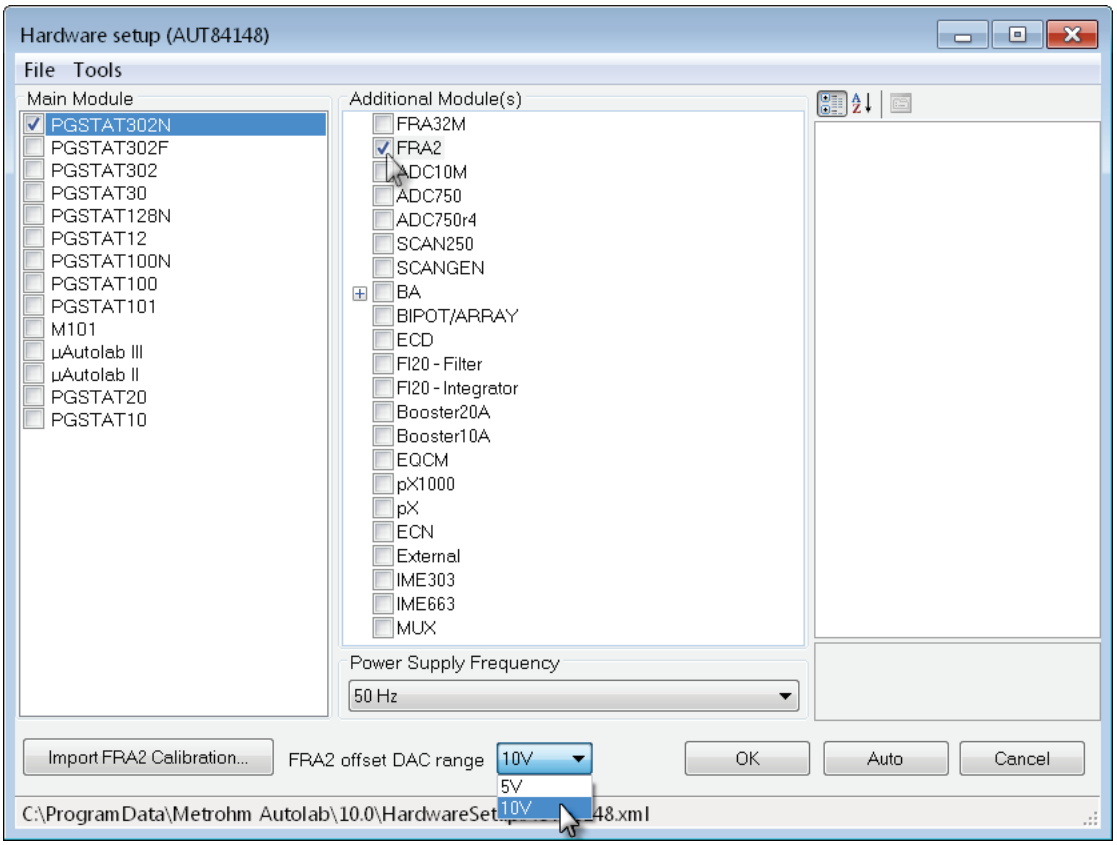


Figure 77 – The 10 V input range can be specified in the Hardware setup directly

Set this toggle to 10 V as shown in Figure 77. Click OK to close the Hardware setup and save the modifications when prompted.

This modification is permanent.

If necessary, new labels (article codes: CAB.LABEL.FRA2..V10.V and CAB.LABEL.FRA2.V10.XY) can be ordered for the modified FRA2 module (see Figure 78).

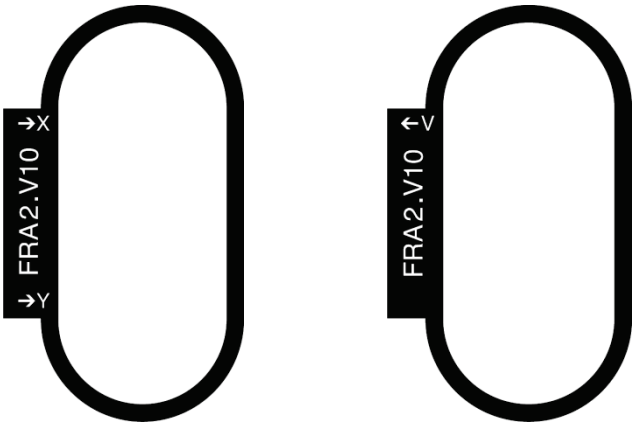


Figure 78 – FRA2 10 V input range labels

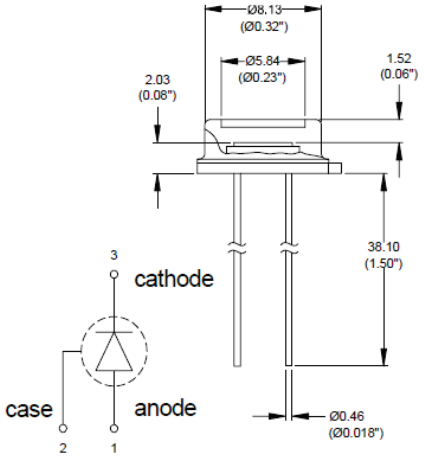
Appendix 2 – Calibrated Photodiode

THORLABS INC
435 Route 206 • P.O. Box 366
Newton, NJ 07860-0366
Ph. 973-579-7227
FAX 973-300-3600

FDS100 Si Photodiode

High Speed
Large Active Area

The FDS100 is a high-speed silicon photodiode with a spectral response from 350nm to over 1100nm. This photodiode has a PIN structure that provides fast rise and fall times with a bias of 20V.

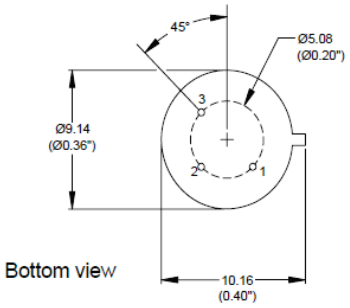


Electrical Characteristics

Spectral Response:	350-1100nm
Active Area:	13.0mm²
Rise Time (RL=50Ω):	10ns (20V bias)
Fall Time (RL=50Ω):	10ns (20V bias)
NEP@900nm:	1.2 x 10^{-14} W/√Hz (@20V bias)
Dark Current:	20nA max (20V)
Package:	T05, 0.36" can

Maximum Ratings

Damage Threshold CW:	100 mW/cm²
Damage 10ns Pulse:	500mJ/cm²
Max Bias Voltage:	25V



Pin Description

1. Detector anode
2. Detector case
3. Detector cathode

The Thorlabs FDS100 photodiode is ideal for measuring both pulsed and CW light sources, by converting the optical power to an electrical current. The Si detector is housed in a T05 can, with an anode, cathode and case connection. The photodiode anode produces a current, which is a function of the incident light power and the wavelength. The responsivity $\Re(\lambda)$, can be read from **Figure 1** to estimate the amount of photocurrent to expect. This can be converted to a voltage by placing a load resistor (R_{LOAD}) from the photodiode anode to the circuit ground. The output voltage is derived as:

$$Vo = P * \Re(\lambda) * R_{LOAD}$$

The bandwidth, f_{BW}, and the rise time response, t_R, are determined from the diode capacitance, C_J, and the load resistance, R_{LOAD}, as shown below. Placing a bias voltage from the photo diode cathode to the circuit ground can lower the photo diode capacitance.

$$f_{BW} = 1/(2\pi * R_{LOAD} * CJ),\ t_R = 0.35/f_{BW}$$

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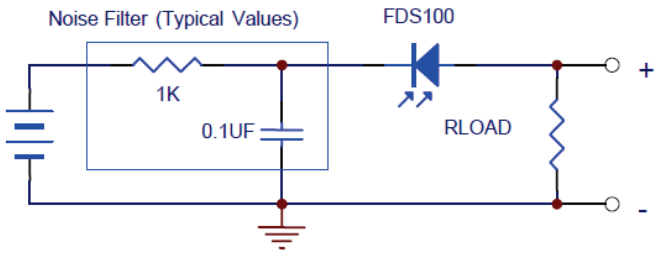
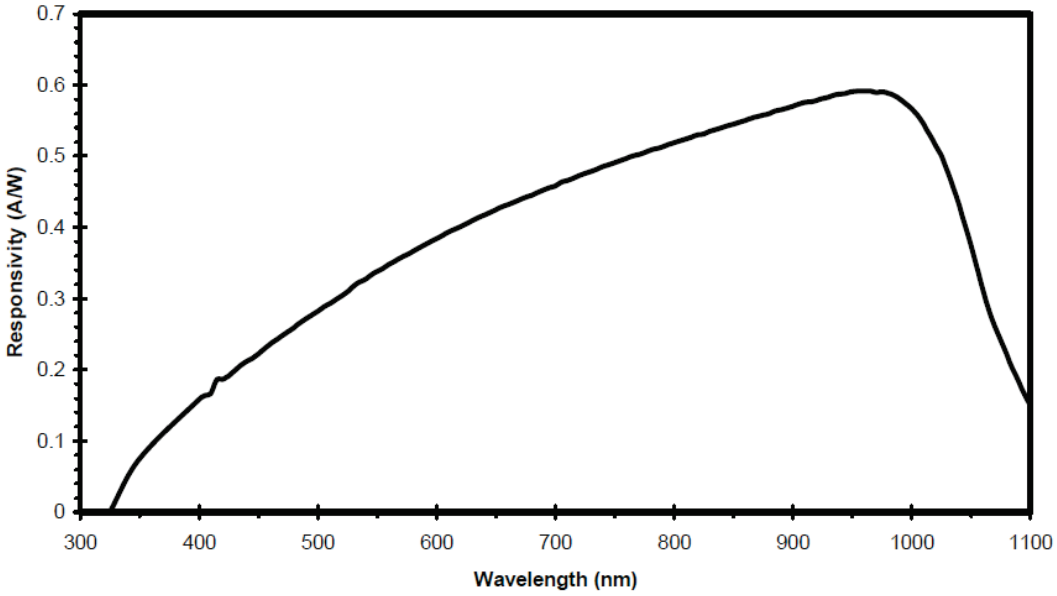
Typical Circuit Diagram



Typical Plots

Figure 1 - FDS100 Spectral Responsivity Curve



Typical Responsivity Curve using Thorlabs calibration services.

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Appendix 3 – Hardware specifications

The specifications of the Autolab LED Driver kit are listed in Table 3.

Power supply	18 V, 1.2 A
Maximum current	1000 mA
Maximum LED current	700 mA
Input voltage range	90 mV – 10 V
Output voltage range	0 mV – 1000 mV
Maximum modulation amplitude	5 V (TOP)
Maximum modulation frequency	20 kHz
Operating temperature	0 – 40 °C

Table 3 – Specifications of the Autolab LED Driver

07/2012

Kanaalweg 29/G
3526 KM Utrecht
The Netherlands

Metrohm
Autolab B.V.